

PHENIX Focus: Hadron Production

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Ground Rules

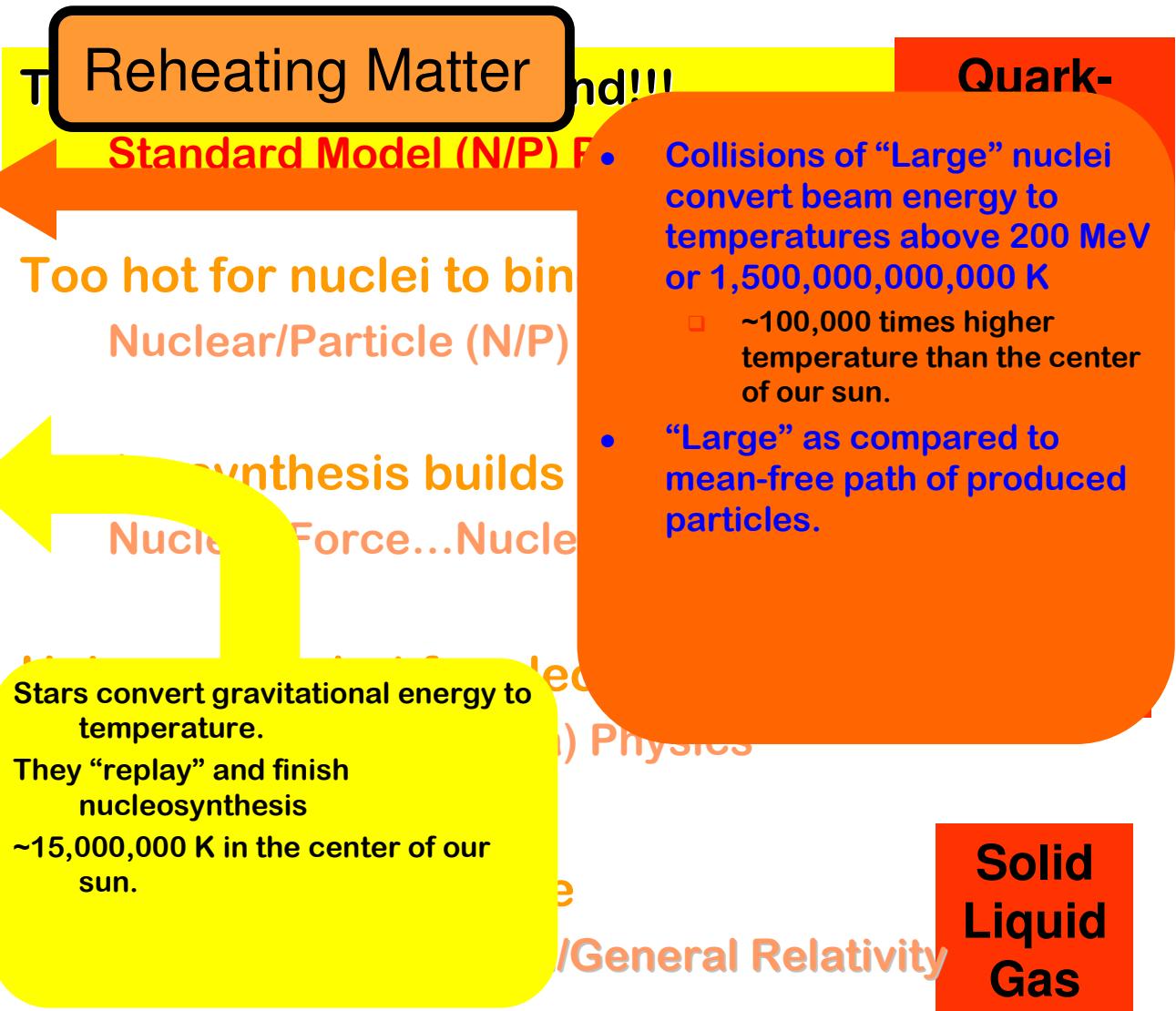
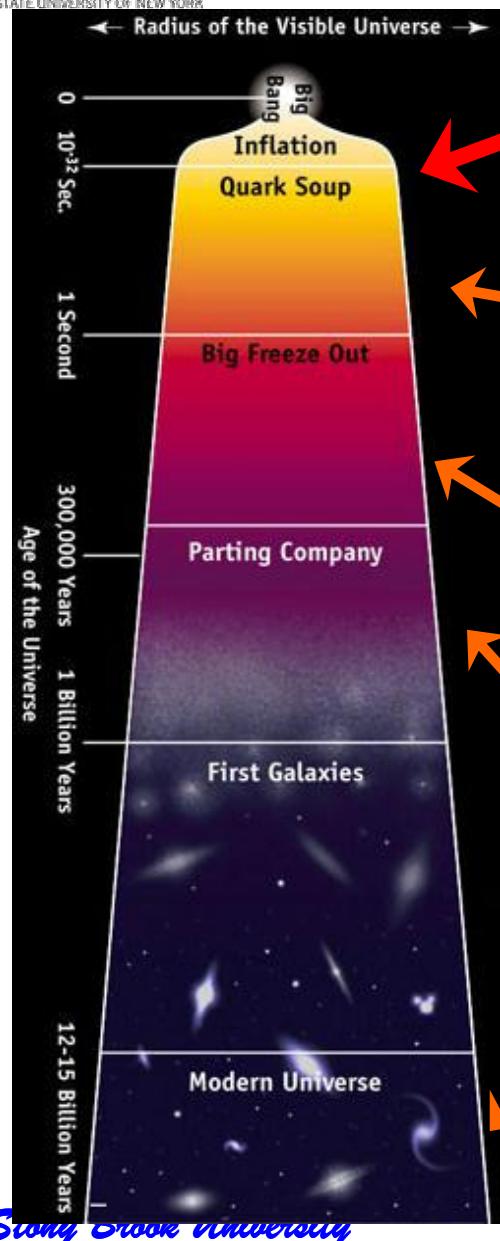
- As explained to me by our host (Henner)
 - “The idea is to have basic, lecture-like talks of one hour for students and postdocs with the intention to discuss physics topics that PHENIX is working on or that are interesting for our research”. The talk should be in a broader scope, i.e. beyond discussing PHENIX/RHIC results.”
- My (possibly inaccurate) interpretation:
 - Don’t fill a talk with a lot of data (and certainly not only PHENIX data), but try to give some context to the data and understanding.
- The topic of the talk should be:
 - Hadron Production.

- **Nearly every measurement we make is of hadrons!**
 - $J/\Psi \rightarrow \mu\mu$ or $ee \dots J/\Psi$ is a hadron.
 - $\pi^0 \rightarrow \gamma\gamma \dots$ is a hadron.
- **Direct photons are not hadrons (but SOOO COOL!)**
- **Almost everything would be fair game.**
- **DECISION:**
 - I will give an overview of many topics with not so much data to drown in, but more discussion of what are all these terms that people often use.
 - ◆ Outline is basically “White paper” plus some updates...
 - ◆ NOTE: Most people are not around for whole run, so overlap from this talk to another is a **GOOD THING!**
 - We can deviate from the slides, **PLEASE INTERRUPT(!!)** this is the best recipe to make the next 6 hours (ummm... one hour) worthwhile...

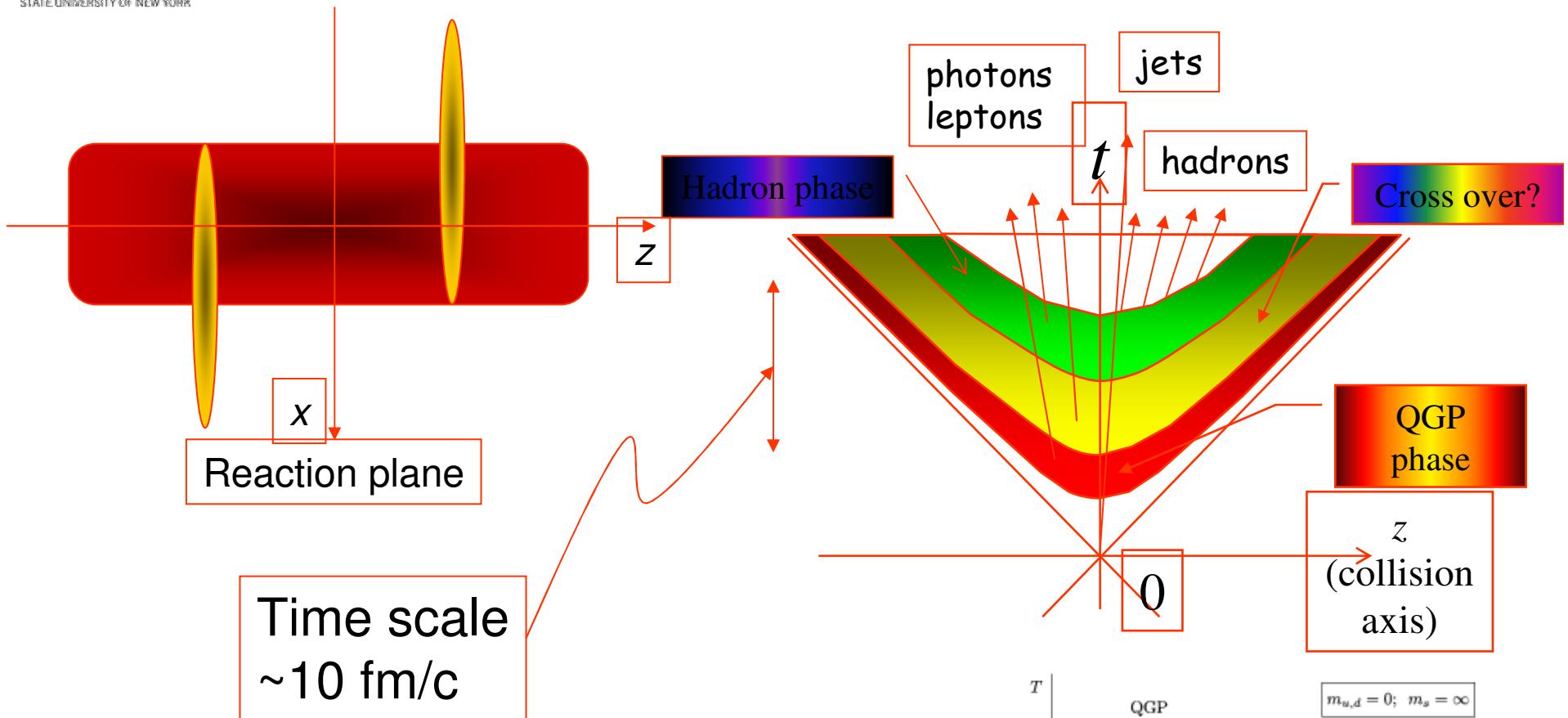
Outline of Lecture

- Are we in the Ballpark?
 - Energy Density
 - Chemical Equilibrium
 - Kinetic Equilibrium
- Is There a There There?
 - The Medium & The Probe
 - High Pt Suppression
 - Control Experiments: dAu, γ_{direct}
- What is It Like?
 - Azimuthally Anisotropic Flow
 - Hydrodynamic Limit
 - Recombination
- Hot new results...
 - Charm Spectral Modification
 - J/Y suppression(?)
 - Volcano Jet Shapes.
 - Direct Photons

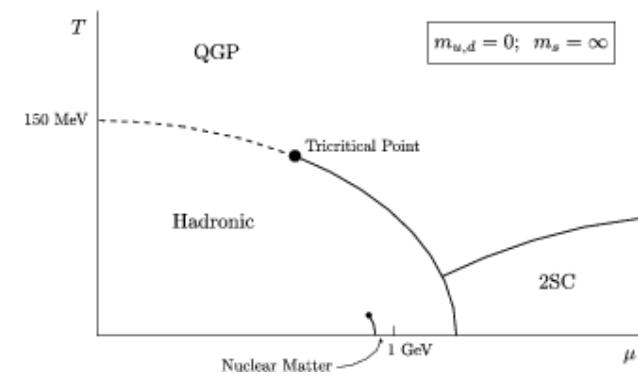
Broad(est) Context



Time Evolution Cartoon

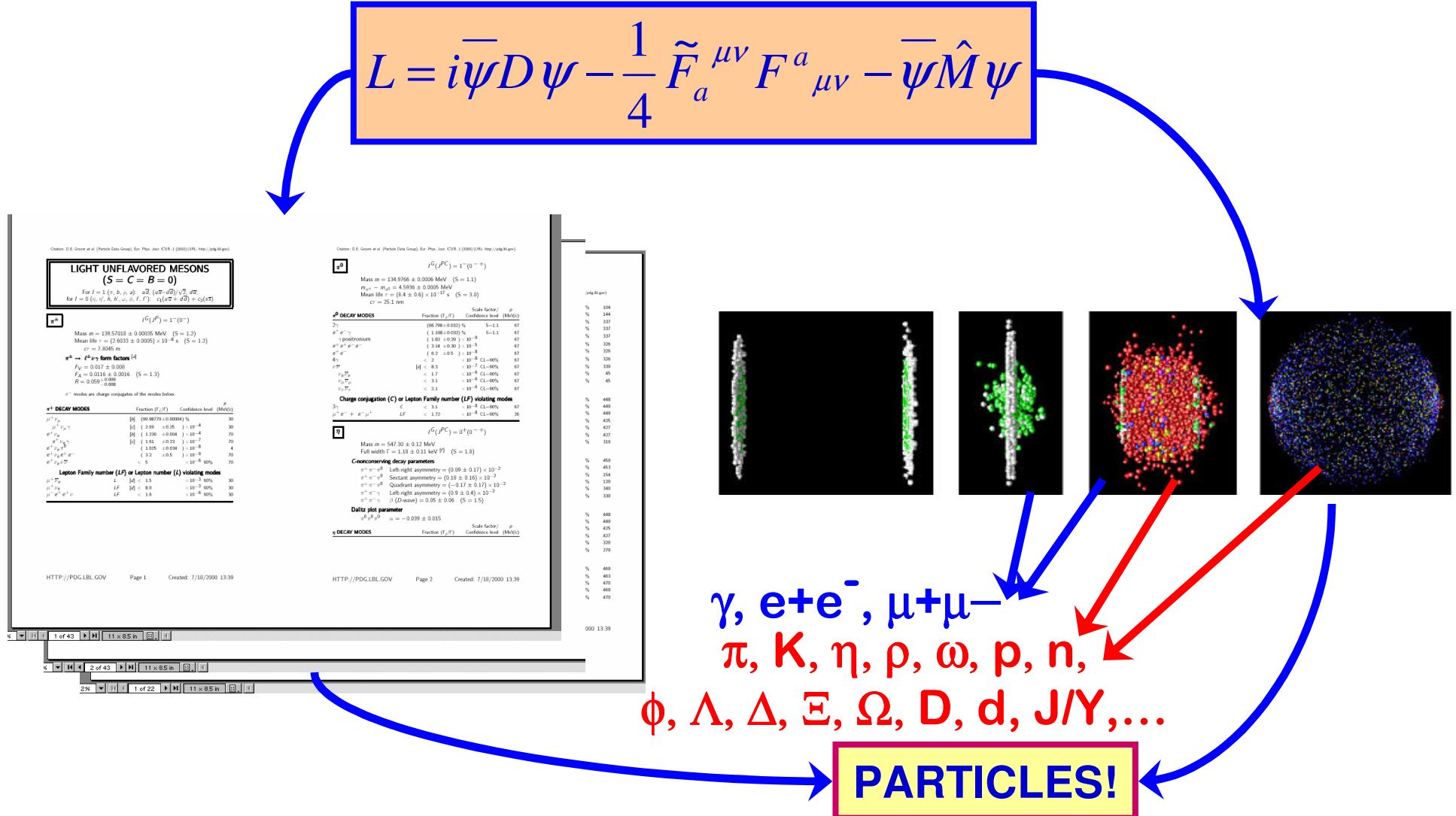


- We establish experimental limits on the ε , T , and density (μ_B).
- Final State = lower bound



Nature's providence

How can we hope to study such a complex system?



- Energy Density defined as

$$\varepsilon \equiv \frac{\text{Energy}}{\text{Volume}} \quad (\text{in } P=0 \text{ frame})$$

- Let's calculate the Mass overlap Energy:

$$\langle \varepsilon \rangle = 2\rho_0\gamma^2 = 3150 \frac{\text{GeV}}{\text{fm}^3} \quad \rho_0 = 0.14 \frac{\text{GeV}}{\text{fm}^3}; \gamma_{RHIC} = 106$$

- That was Meaningless Drivel !!!!:
 - Same result with or without interactions.
 - In the absence of interactions goes from zero to this and back in $t_p = 2R/\gamma$!!
 - Only enough time for $Q > 1.5 \text{ GeV}/c$ processes!!
- We shall choose to ignore entirely all mass energy from the initial nuclei...apply considerations ONLY for $t > 2R/\gamma = 0.13 \text{ fm}/c$

- At $t=t_{\text{form}}$, the hatched volume contains all particles w/ $b < dz/t_{\text{form}}$:

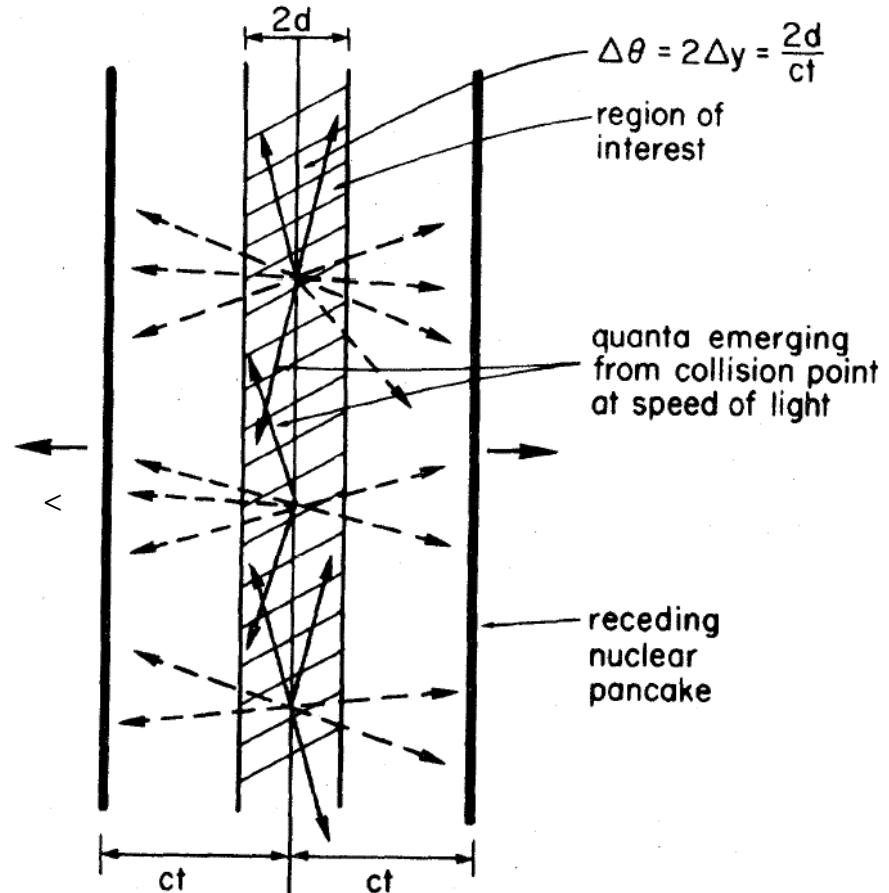
$$dN = \frac{dz}{t_{\text{form}}} \frac{dN}{d\beta_{||}} = \frac{dz}{t_{\text{form}}} \frac{dN}{dy}; (dy = d\beta_{||} @ y=0)$$

- At $y=b_{||}=0$, $E=m_T$, thus:

$$\langle \epsilon(t_{\text{form}}) \rangle = \frac{E}{V} = \frac{dN \langle m_T \rangle}{dz \cdot A} = \frac{dN(t_{\text{form}})}{dy} \frac{\langle m_T \rangle}{t_{\text{form}} \cdot A}$$

- We can equate $dN \langle m_T \rangle$ & dE_T and have:

$$\langle \epsilon_{BJ}(t_{\text{form}}) \rangle = \frac{1}{t_{\text{form}} \cdot A} \frac{dE_T(t_{\text{form}})}{dy}$$



Two nuclei pass through one another leaving a region of produced particles between them.

- The previous result, is known as the “Nominal Bjorken Energy density and is commonly applied at many energies.
- However, the result is **NOT MEANINGFUL** unless the condition $t > 2R/\gamma$ is satisfied. While this is true at RHIC, it is **most certainly not** for lower energies such as SPS experiments and AGS experiments. $\sqrt{s_{NN}} = 5\text{Gev}(17\text{GeV})$, respectively
- Additionally, Bjorken used $t_{\text{form}} = 1 \text{ fm/c}$ as an order of magnitude estimate.
- To use the Bjorken formula in a meaningful way, we should attempt to experimentally determine a formation time.

Just to form the particles:

- We can construct a simple estimate of the formation time via the uncertainty principle:

$$t_{form} = \frac{\hbar}{\langle m_T \rangle}$$

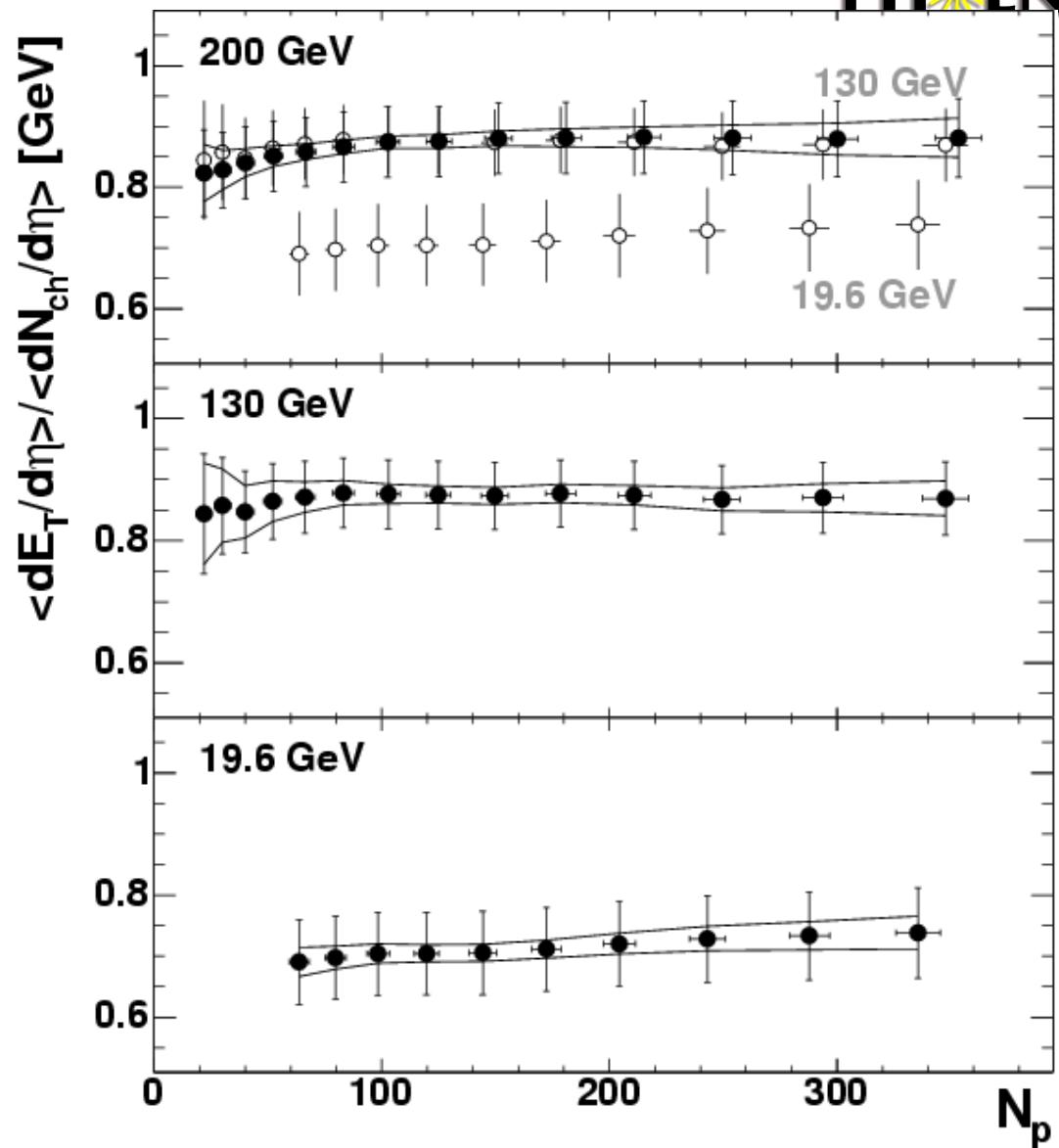
- The average transverse mass at formation time cannot be measured. However, using the final state value can only lead to an eventual underestimate of the energy density:

$$\langle m_T \rangle = \frac{\frac{dE_T(t_{form})}{dy}}{\frac{dN(t_{form})}{dy}} \leq \frac{\frac{dE_T}{dy}}{\frac{dN}{dy}}(t_{final})$$

Formation time

- Notice that only charged particles are measured for multiplicity.
- Adjusting for missing yield results in an upper bound on formation time of

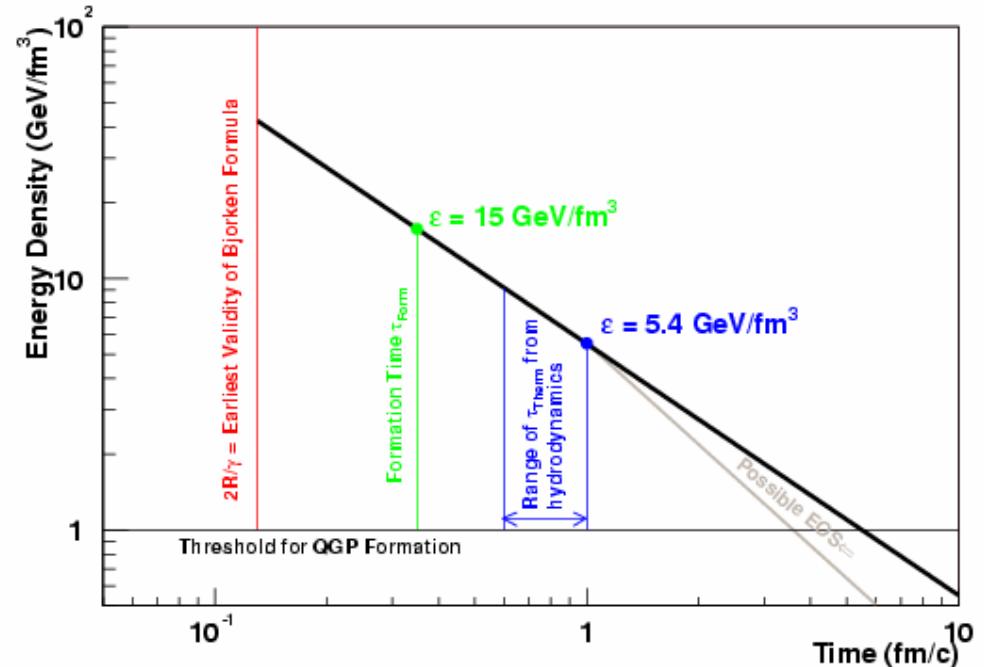
$$t_{form} \cong 0.35 \frac{fm}{c}$$



Initial Energy density

Summary:

- Two values of τ_0 :
 - $\tau_{\text{form}} = \hbar / \langle m_T \rangle (\tau_{\text{form}}) \leq \hbar / \langle m_T \rangle^{\text{final}} = 0.35 \text{ fm/c}$
 - $\tau_{\text{therm}} \leq 1 \text{ fm/c}$ (hydro)
 - We derive conservative *lower limits* on the energy density at formation and thermalization
 - $\varepsilon(\text{form}) > 15 \text{ GeV/fm}^3$
 - $\varepsilon(\text{therm}) > 5.4 \text{ GeV/fm}^3$
- in central Au+Au collision at 200 GeV



These values are well in excess of $\sim 1 \text{ GeV/fm}^3$ obtained in lattice QCD as the energy density needed to form a deconfined phase.

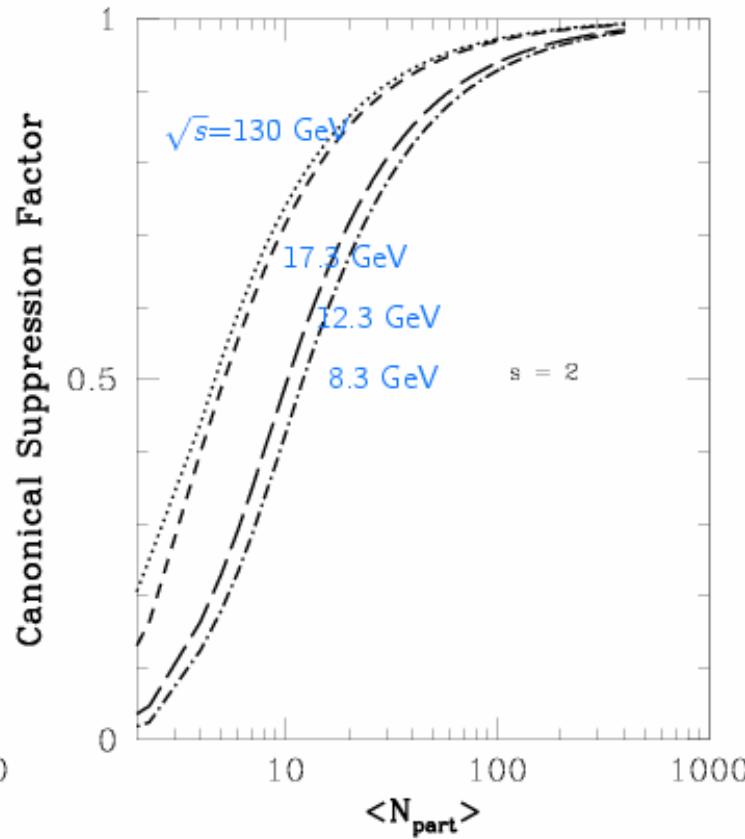
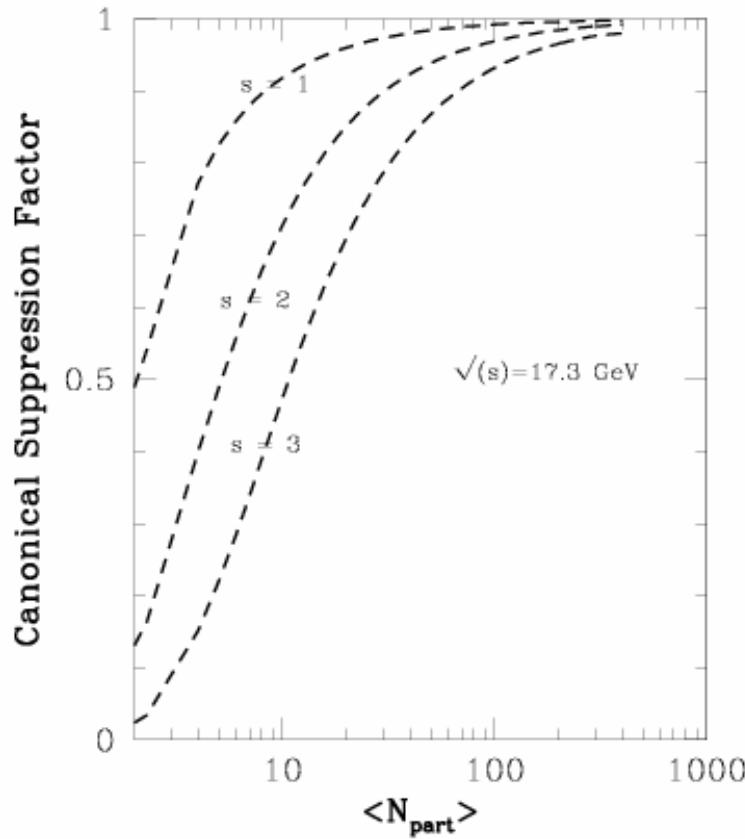
Thermal Equilibrium

- We'll consider two aspects of thermal considerations:

- Chemical Equilibrium
 - ◆ Are all particle species produced at the right relative abundances?
- Kinetic Equilibrium
 - ◆ Energetic sconsistent with common temperature plus flow velocity?
- Choose appropriate statistical ensemble:
 - Grand Canonical Ensemble: In a large system with many produced particles we can implement conservation laws in an averaged sense via appropriate chemical potentials.
 - Canonical Ensemble: in a small system, conservation laws must be implemented on an EVENT-BY-EVENT basis. This makes for a severe restriction of available phase space resulting in the so-called “Canonical Suppression.”
 - Where is canonical required:
 - ◆ low energy HI collisions.
 - ◆ high energy e+e- or hh collisions
 - ◆ Peripheral high energy HI collisions

Canonical Suppression

Tounsi and Redlich, hep-ph/0211159



for $N_{\text{part}} \geq 60$ Grand Canonical ok to better 10%

Canonical Suppression is likely the driving force
behind “strangeness enhancement”

- The formula for the number density of all species:

$$n_i^0 = \frac{g_i}{2\pi^2} \int \frac{p^2 dp}{e^{(E - \mu_B B_i - \mu_s S_i - \mu_3 I^3)/T} \pm 1}$$

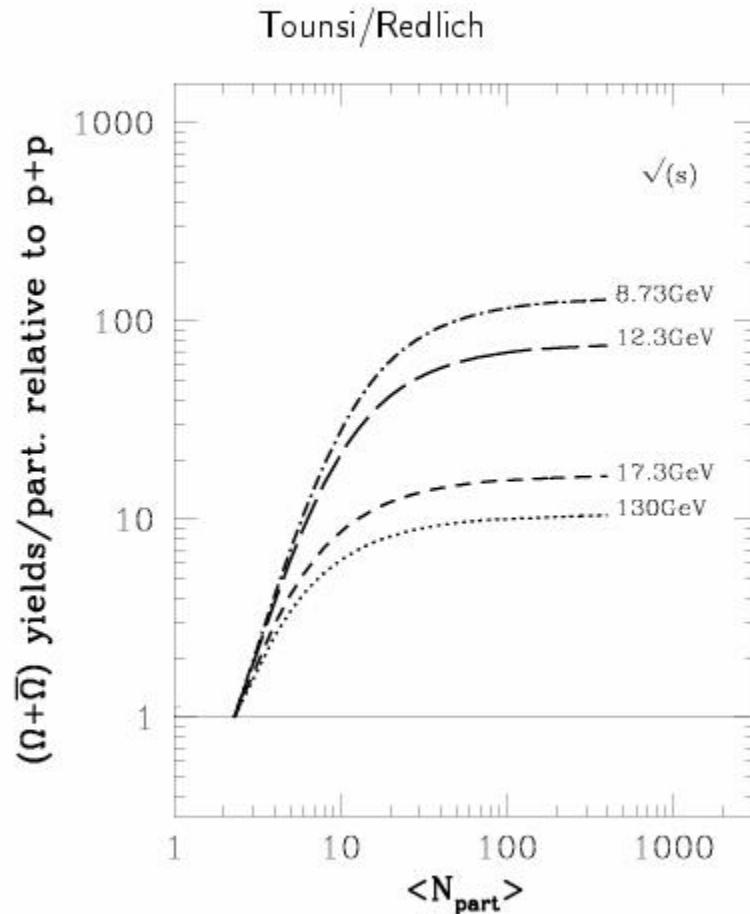
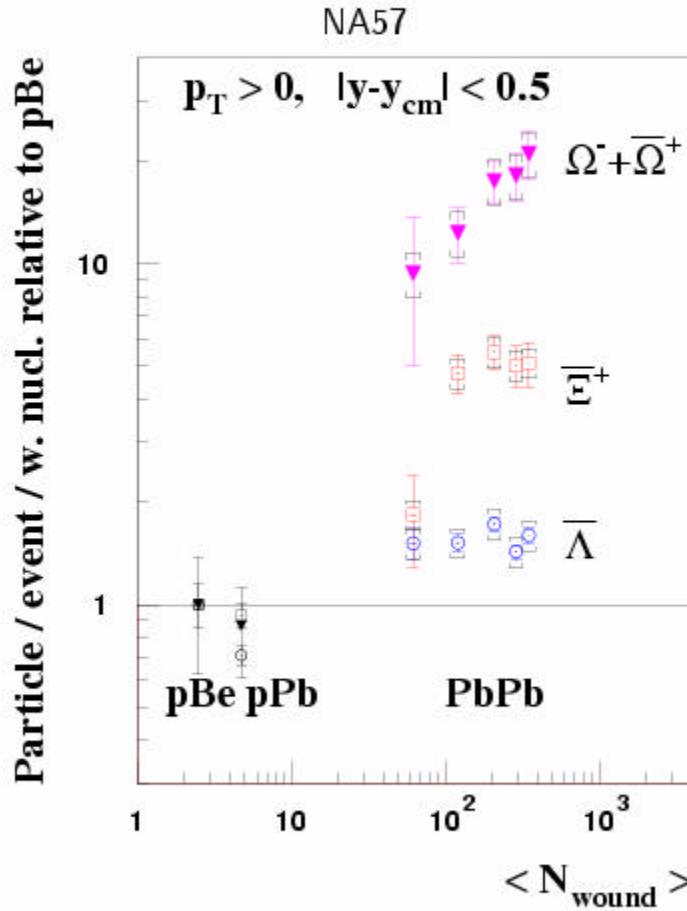
here g_i is the degeneracy

$$E^2 = p^2 + m^2$$

μ_B , μ_s , μ_3 are baryon, strangeness, and isospin chemical potentials respectively.

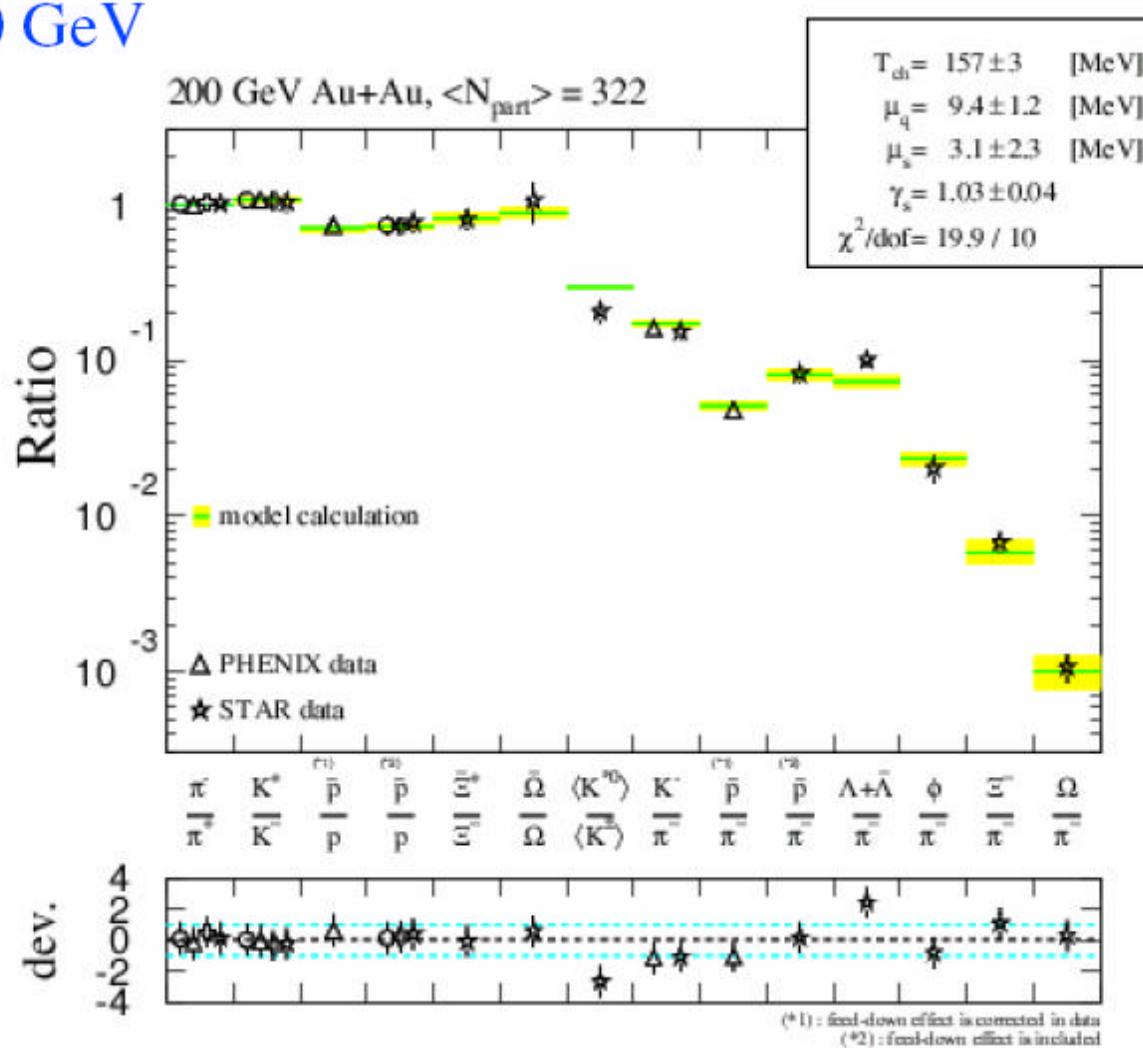
- Given the temperature and all m , one determines the equilibrium number densities of all various species.
- The ratios of produced particle yields between various species can be fitted to determine T , μ .

Strangeness Enhancement in 158 A GeV/c Pb + Pb Collisions



Ω enhancement central ok. but doesn't flatten at $N_{part} = 100$

200 GeV



- For any interacting system of particles expanding into vacuum, flow is a natural consequence.
 - During the cascade process, one naturally develops an ordering of particles with the highest common underlying velocity at the outer edge.
- This motion complicates the interpretation of the momentum of particles as compared to their temperature and should be subtracted.
 - Although 1st principles calculations of fluid dynamics are the higher goal, simple parameterizations are nonetheless instructive.
- Hadrons are released in the final stages of the collision and therefore measure “FREEZE-OUT”

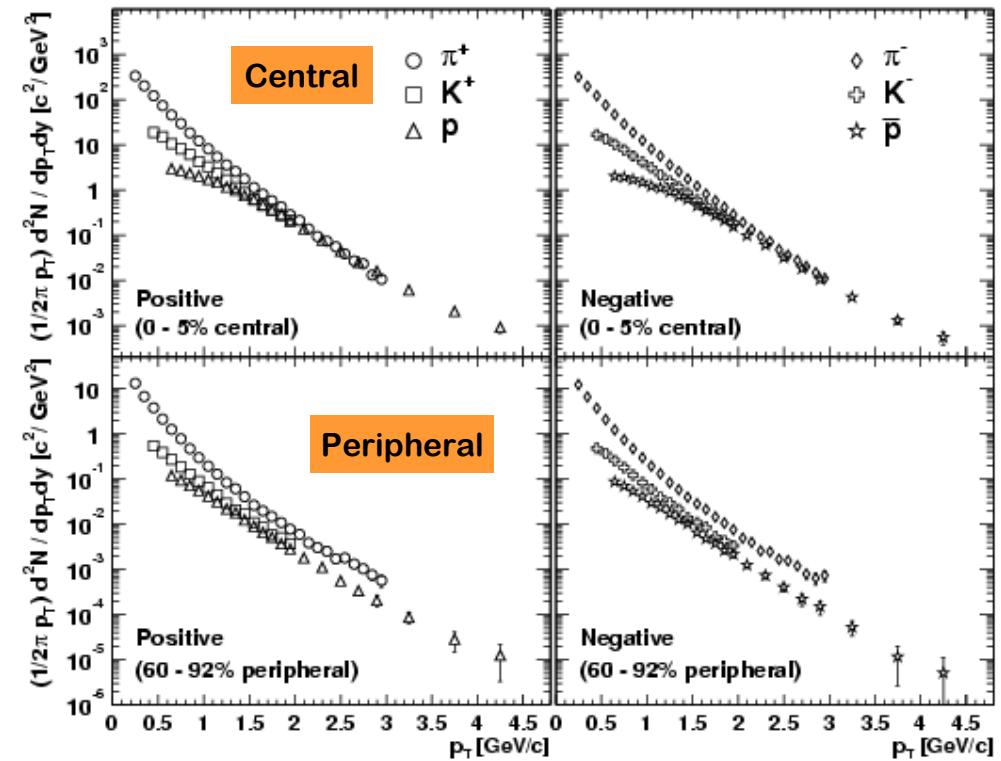
Singles Spectra

- Peripheral:

- Pions are concave due to feeddown.
- K,p are exponential.
- Yields are MASS ORDERED.

- Central:

- Pions still concave.
- K exponential.
- p flattened at left
- Mass ordered wrong (p passes pi !!!)



Underlying collective VELOCITIES
impart more momentum to heavier
species consistent with the basic
trends

- Let's consider a Thermal Boltzmann Source:

$$\frac{d^3N}{dp^3} \propto e^{-E/T}; E \frac{d^3N}{dp^3} = \frac{d^3N}{m_T dm_T d\phi dy} \propto E e^{-E/T} = m_T \cosh(y) e^{-m_T \cosh(y)/T}$$

- If this source is boosted radially with a velocity β_{boost} and evaluated at $y=0$:

$$\frac{1}{m_T} \frac{dN}{dm_T} \propto m_T I_0\left(\frac{p_T \sinh(\rho)}{T}\right) K_1\left(\frac{m_T \cosh(\rho)}{T}\right)$$

where $\rho = \tanh^{-1}(\beta_{\text{boost}})$

- Simple assumption: uniform sphere of radius R and boost velocity varies linearly w/ r:

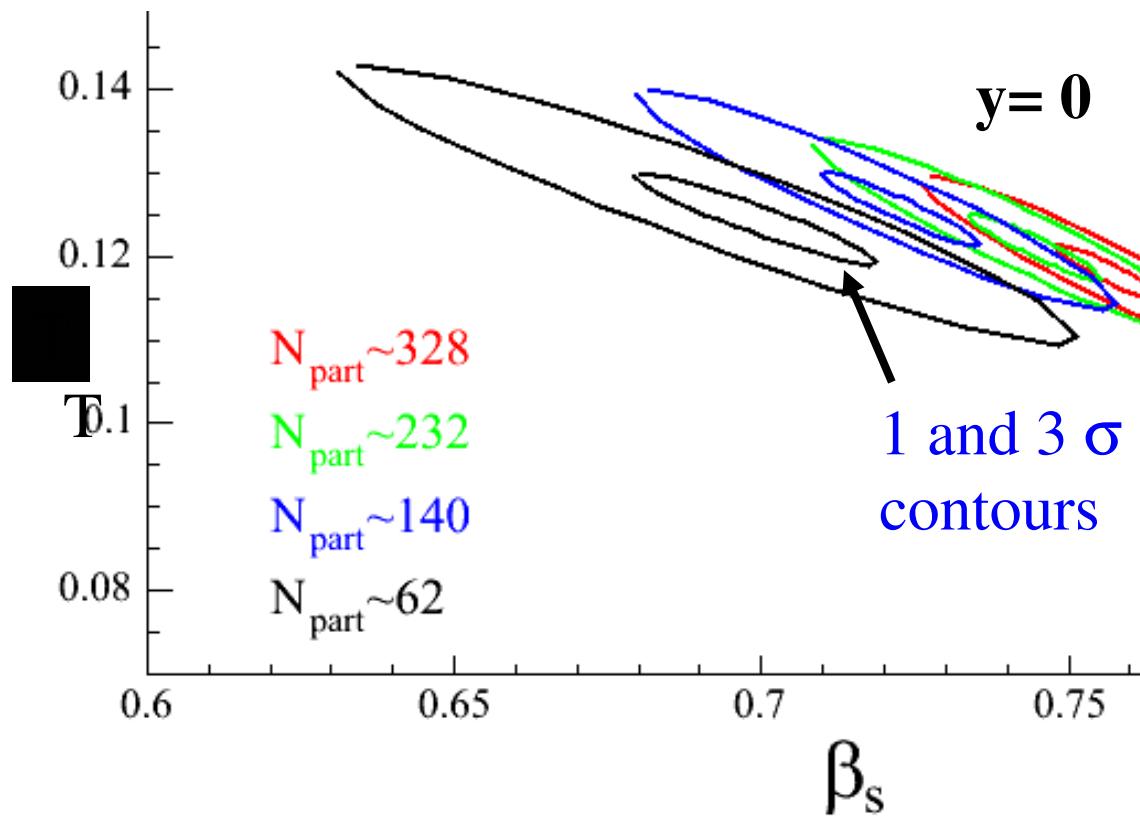
$$\frac{1}{m_T} \frac{dN}{dm_T} \propto \int_0^R r^2 dr m_T I_0\left(\frac{p_T \sinh(\rho)}{T}\right) K_1\left(\frac{m_T \cosh(\rho)}{T}\right)$$

$$\rho(r) = \tanh^{-1}\left(\beta_T^{\text{MAX}} \frac{r}{R}\right)$$

Blast Wave Fits

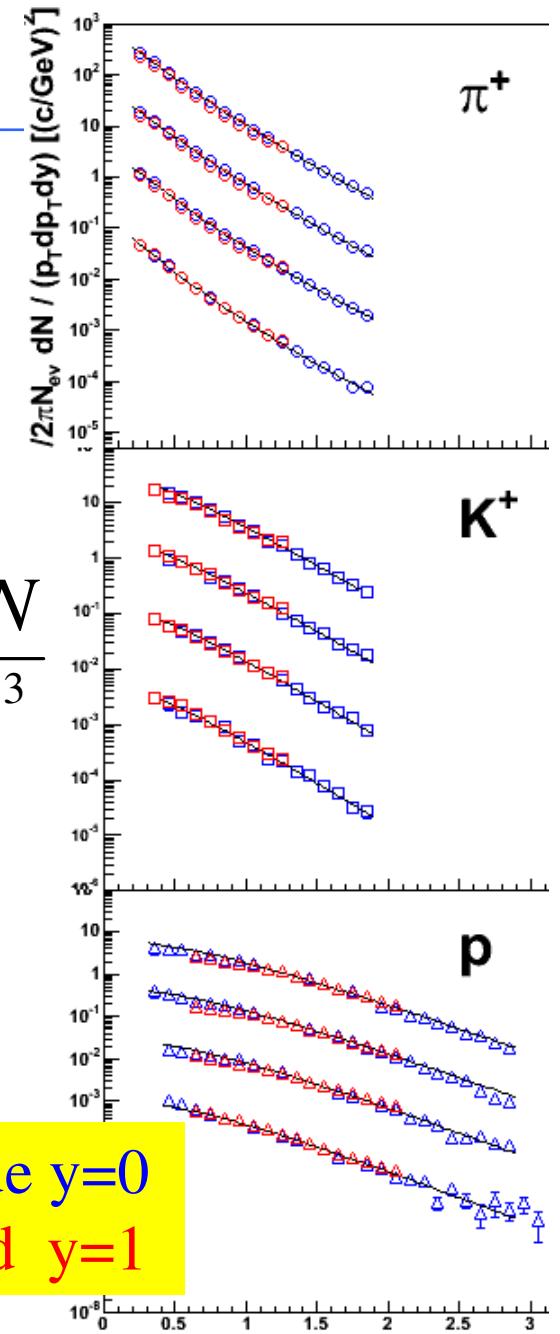
Fit AuAu spectra to blast wave model:

- β_s (surface velocity) drops with $dN/d\eta$
- T (temperature) almost constant.



$$E \frac{d^3 N}{dp^3}$$

Blue $y=0$
Red $y=1$



Thomas R. Hennick

- We accelerate nuclei to high energies with the hope and intent of utilizing the beam energy to drive a phase transition to QGP.
- The collision must not only utilize the energy effectively, but generate the signatures of the new phase for us.
- I will make an artificial distinction as follows:
 - Medium: The bulk of the particles; dominantly soft production and possibly exhibiting some phase.
 - Probe: Particles whose production is calculable, measurable, and thermally incompatible with (distinct from) the medium.
- The medium & probe paradigm will establish whether there is a there there.

The Probes Gallery:

q: fast color triplet

g: fast color octet

Q: slow color triplet

QQbar: slow color singlet/octet

Virtual photon: colorless

Real photon: colorless

Unknown Medium

Induced gluon radiation ?

Energy Loss ?

Dissociation ?

Controls

Jet Suppression

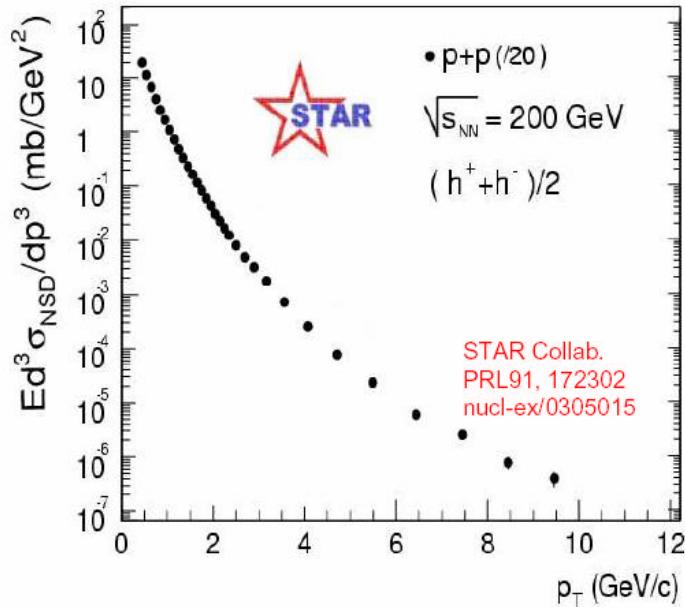
charm/bottom dynamics

J/ Ψ & Y

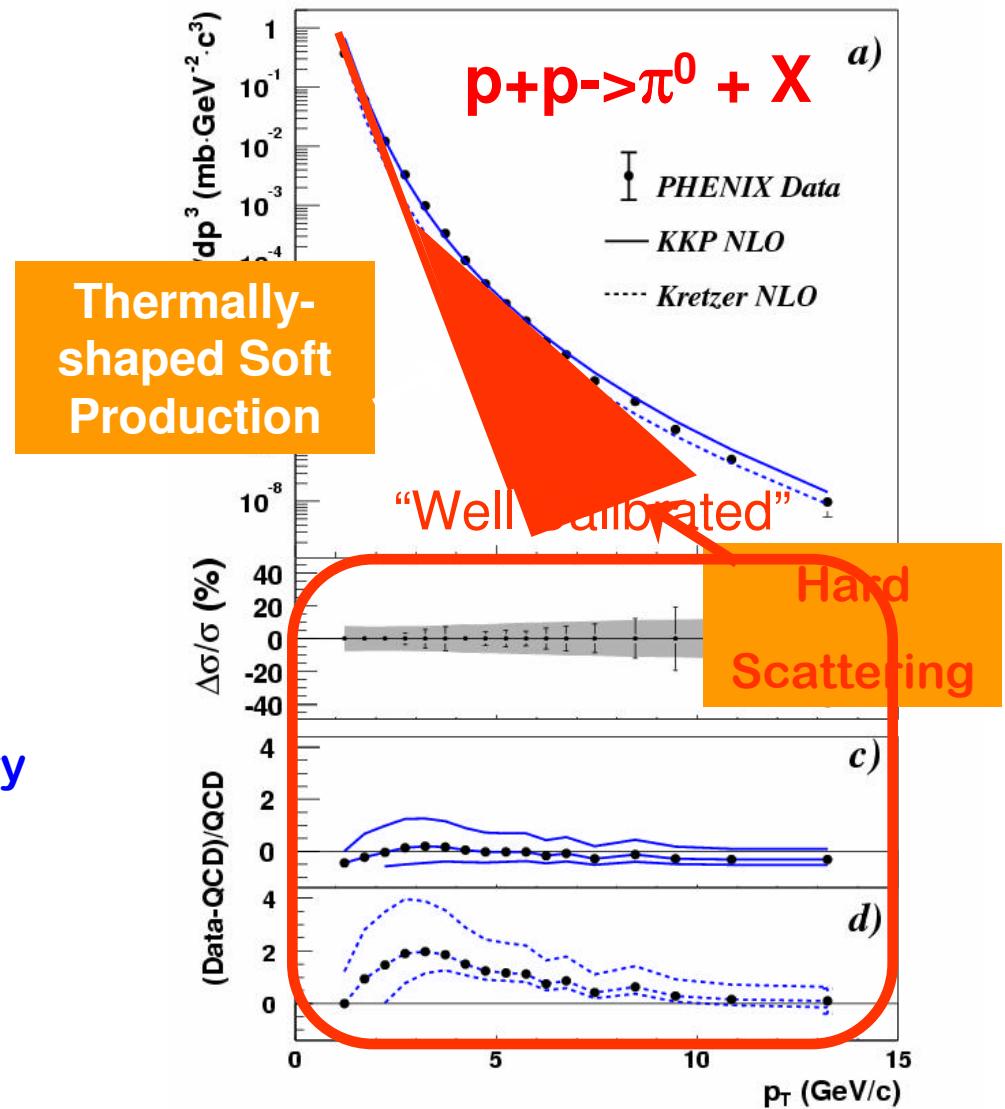
direct photons
CONTROL

The importance of the control measurement(s) cannot be overstated!

Calibrating the Probe(s)

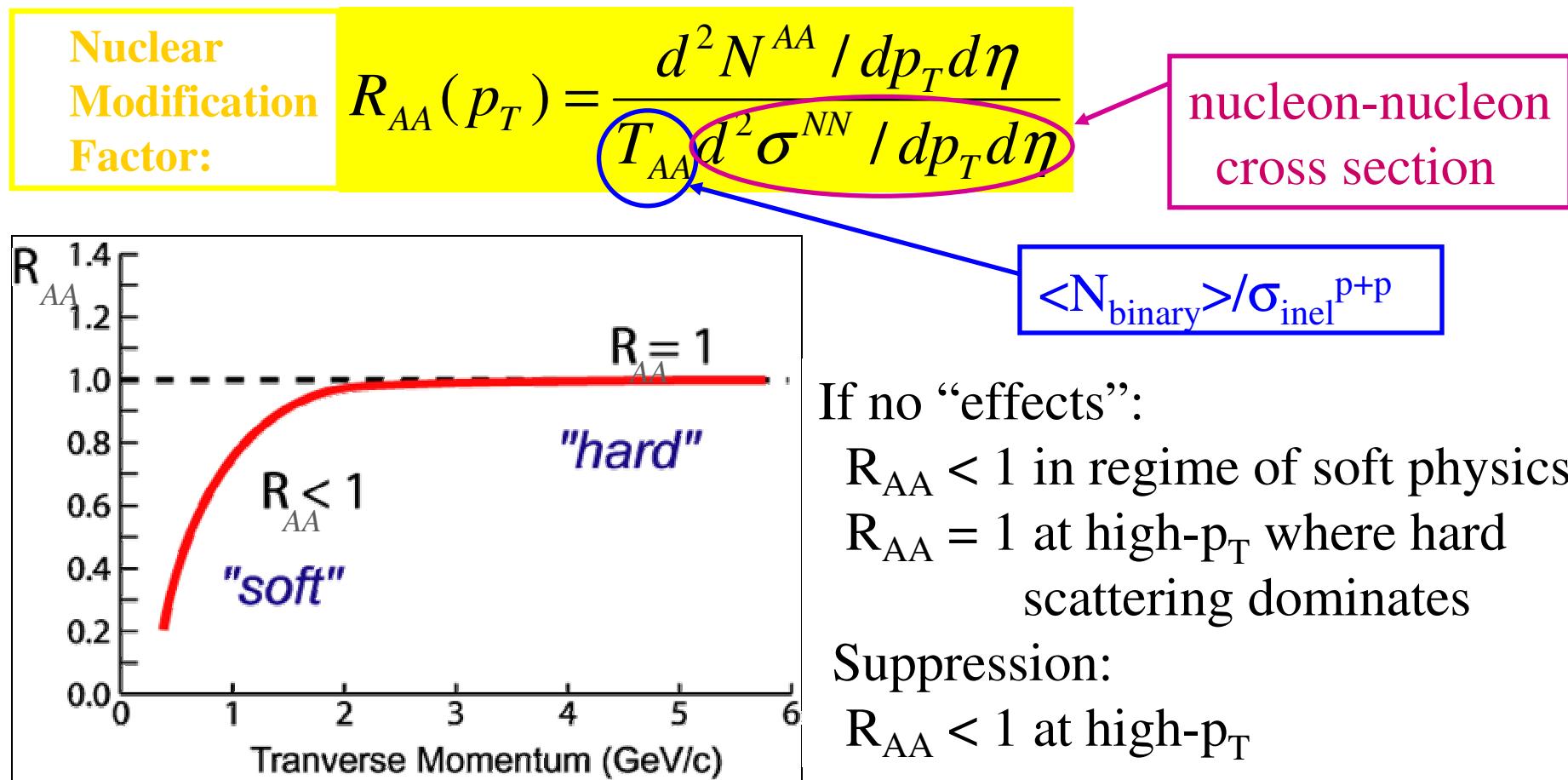


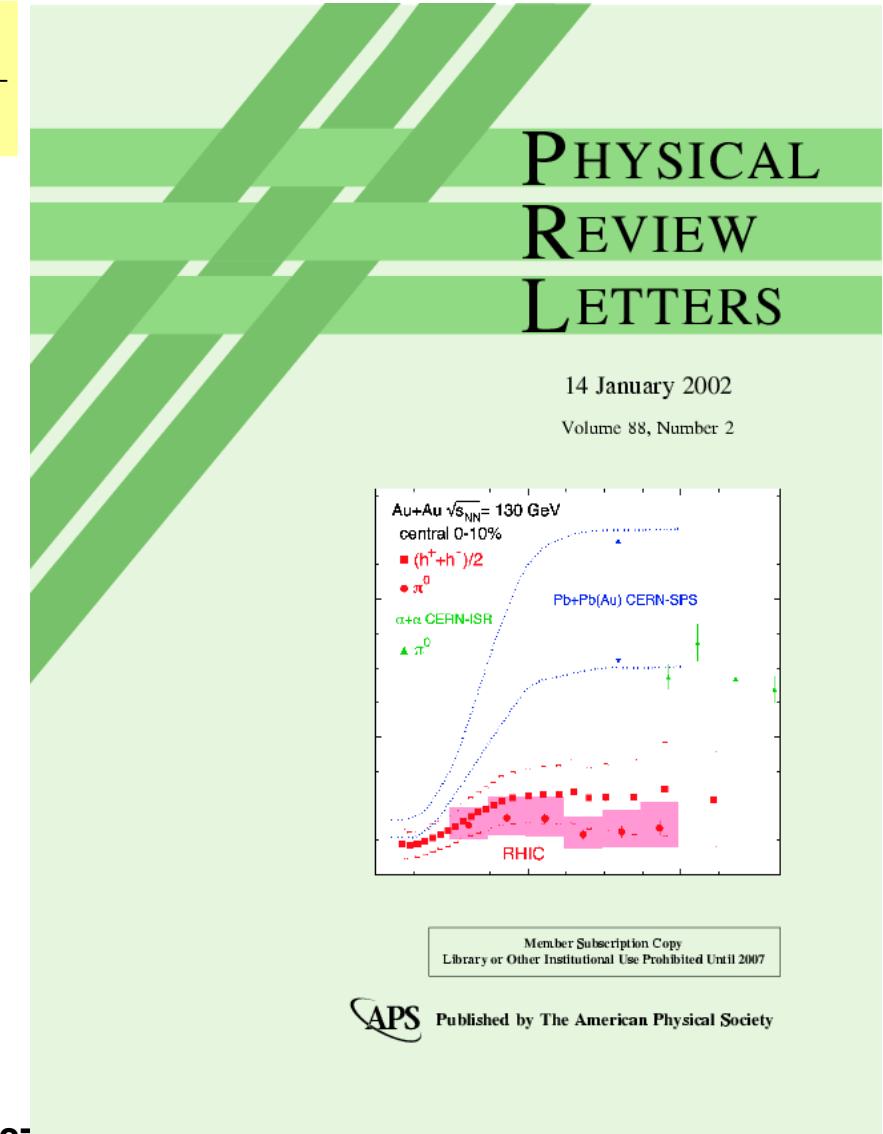
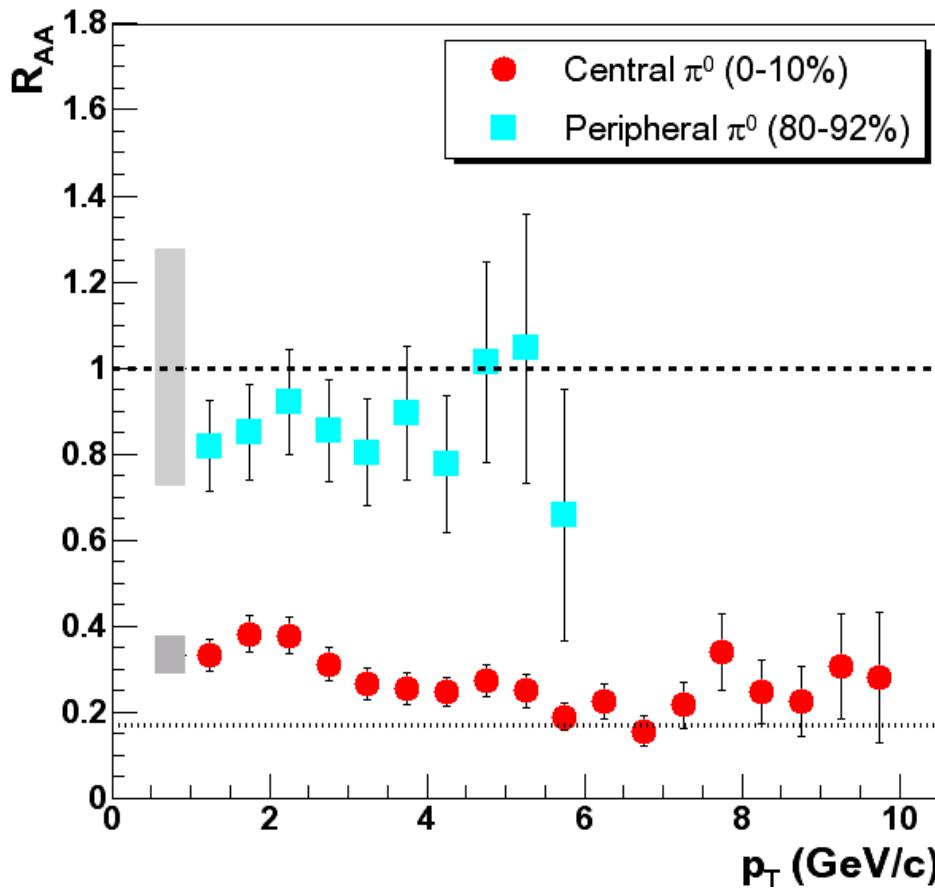
- Measurement from elementary collisions.
- “The tail that wags the dog” (M. Gyulassy)

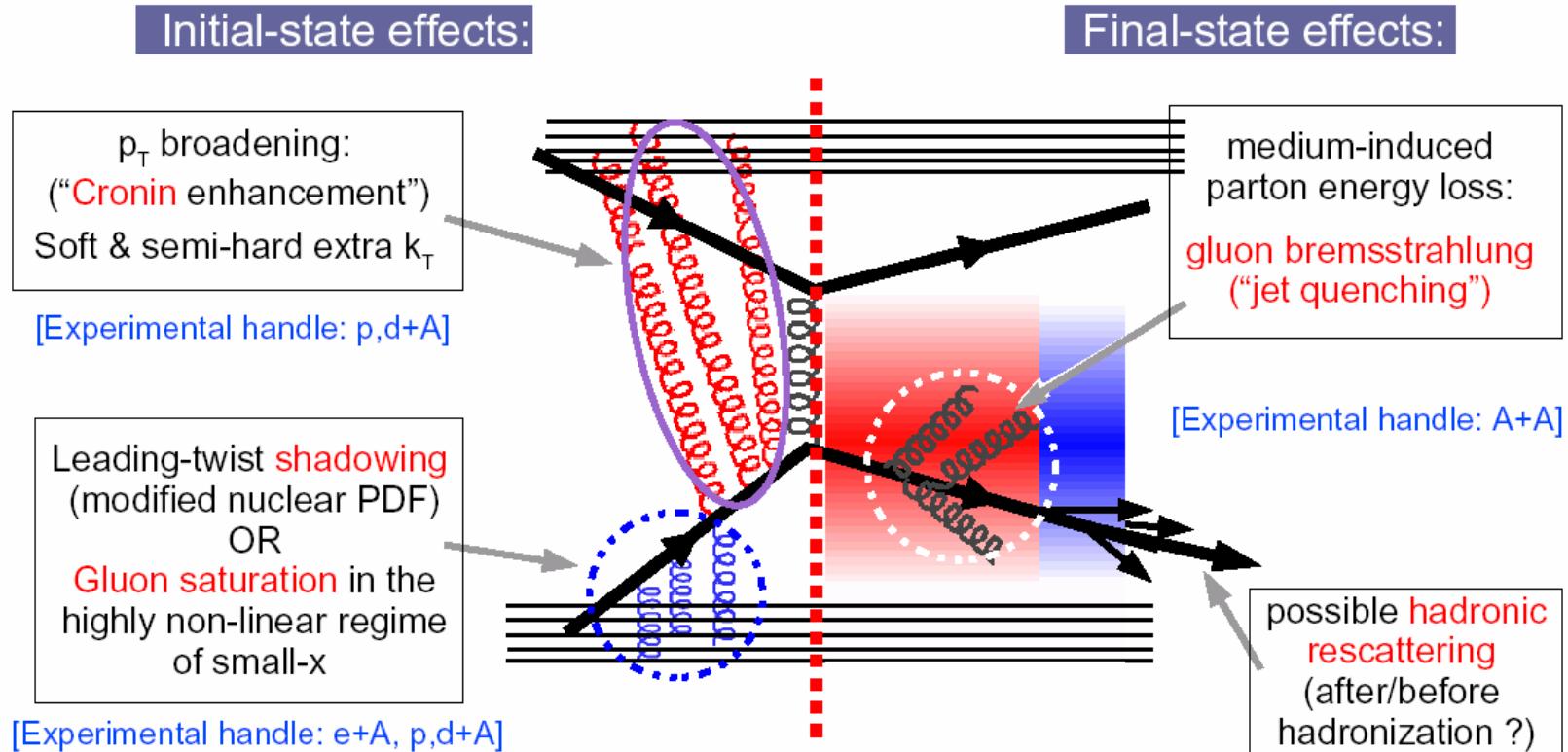


R_{AA} Normalization

1. Compare Au+Au to nucleon-nucleon cross sections
2. Compare Au+Au central/peripheral

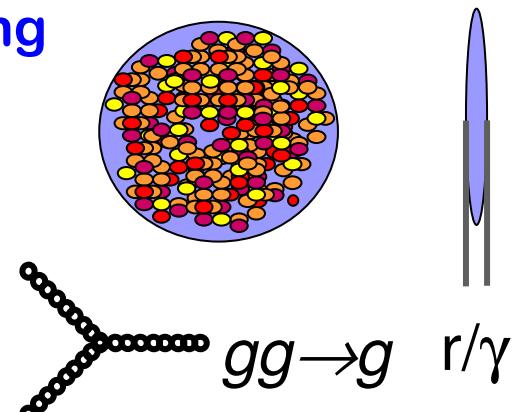




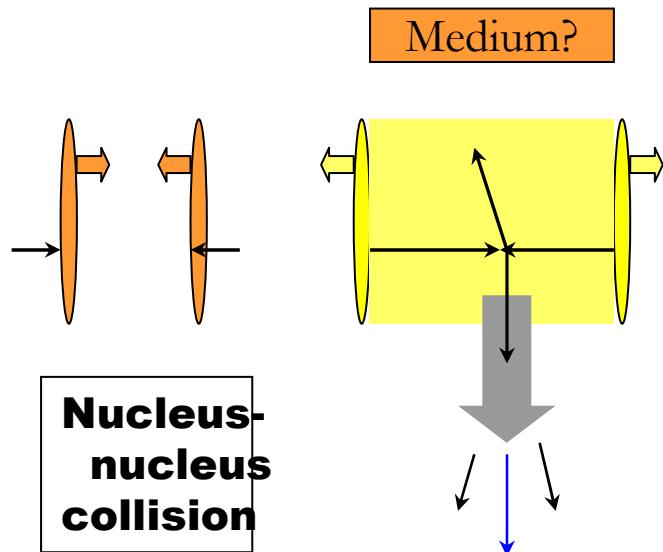


- **Color Glass Condensate**
- **Gluon fusion reduces number of scattering centers in initial state.**
- **Theoretically attractive; limits DGLAP evolution/restores unitarity**

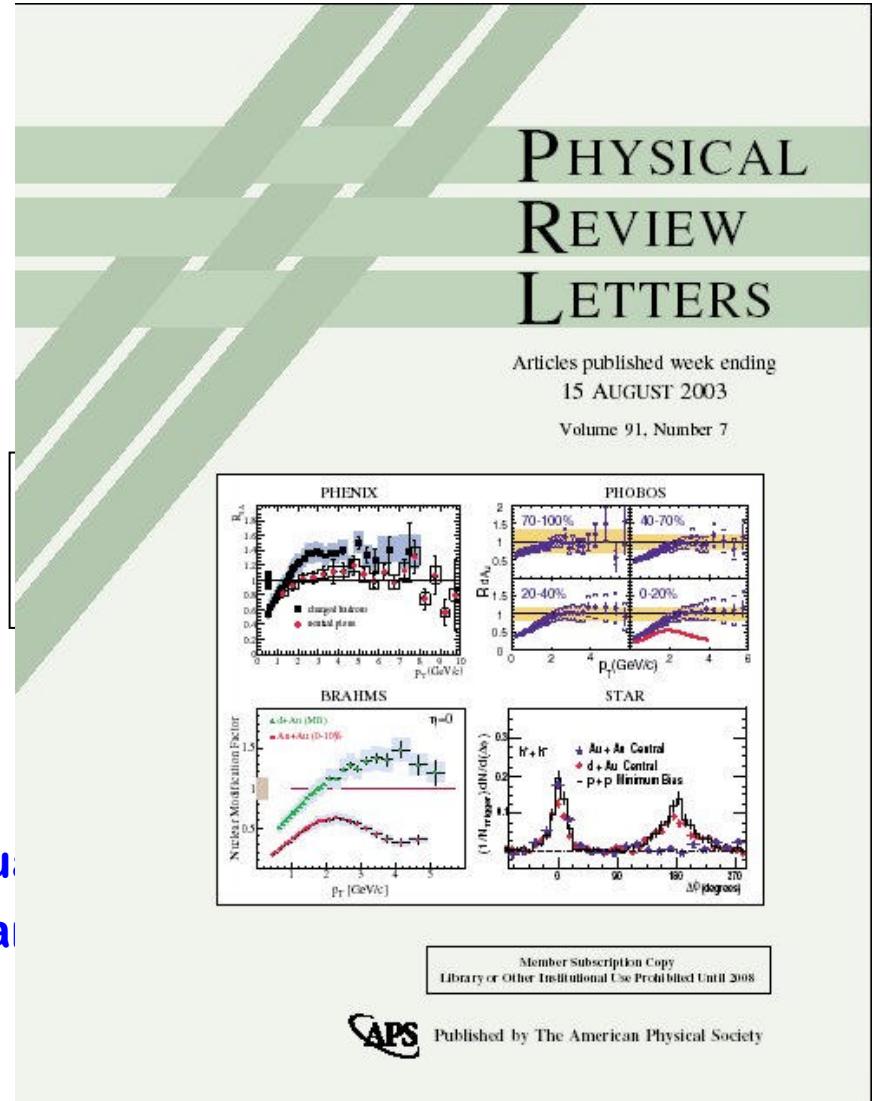
probe rest frame



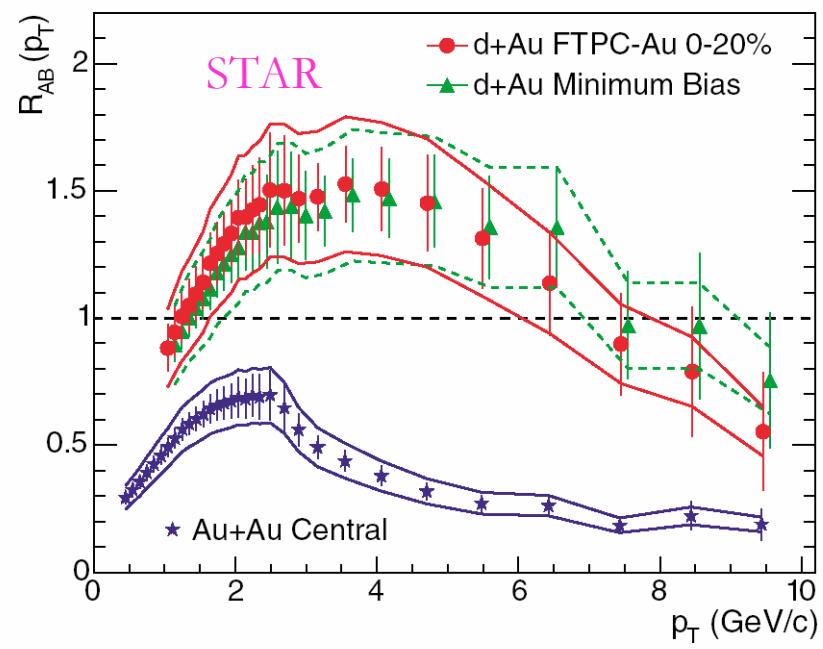
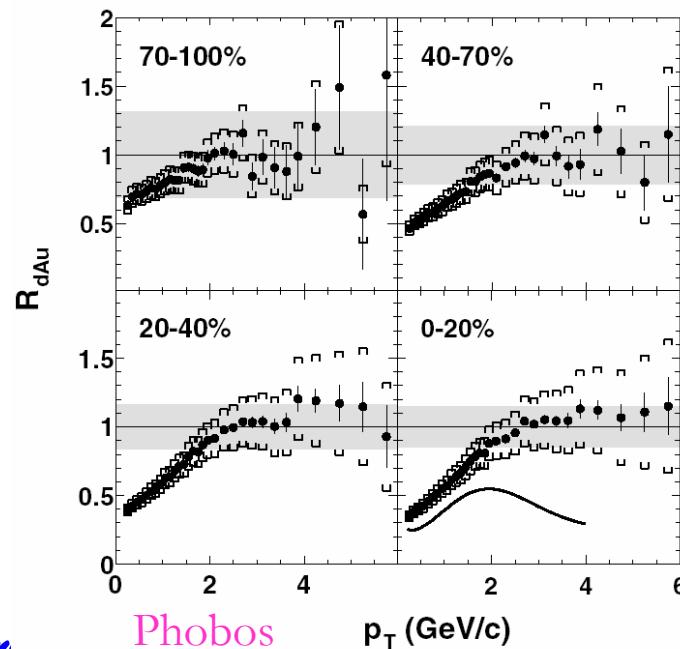
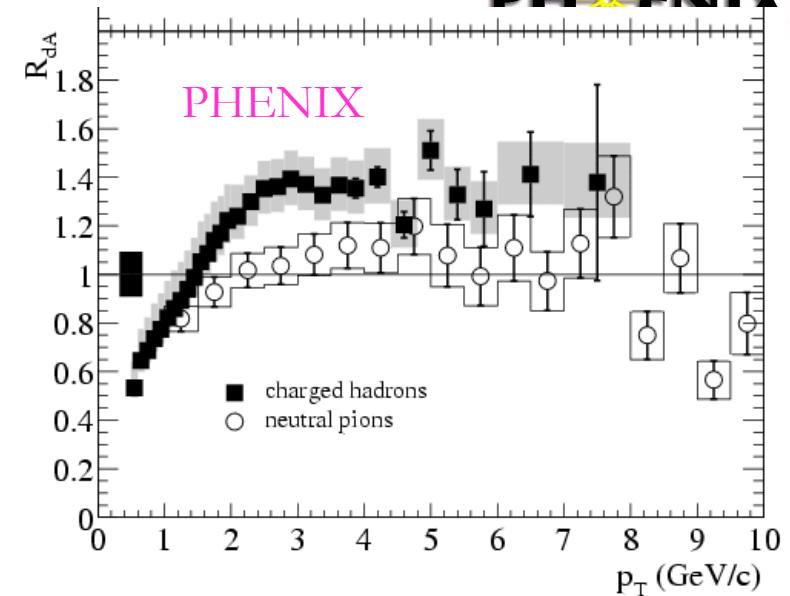
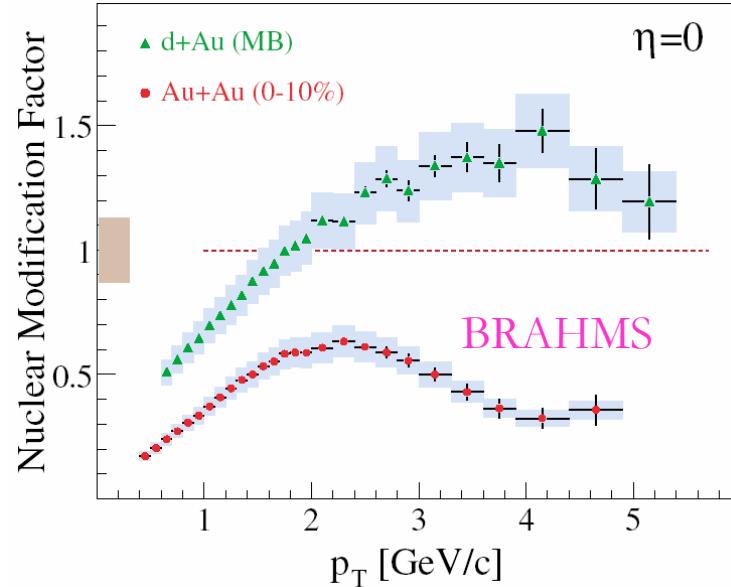
Control Experiment



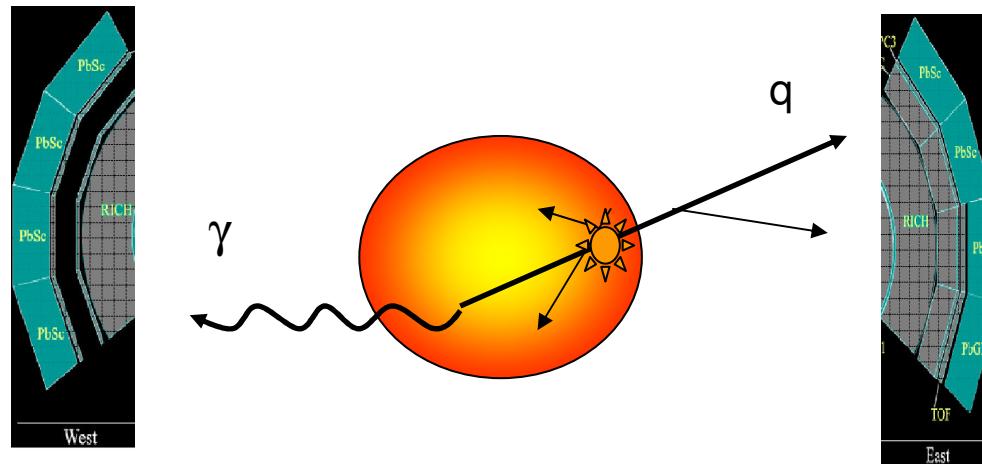
- Collisions of small with large nuclei qualitatively different
- Small + Large distinguishes all initial and final states



NO suppression in d+Au!

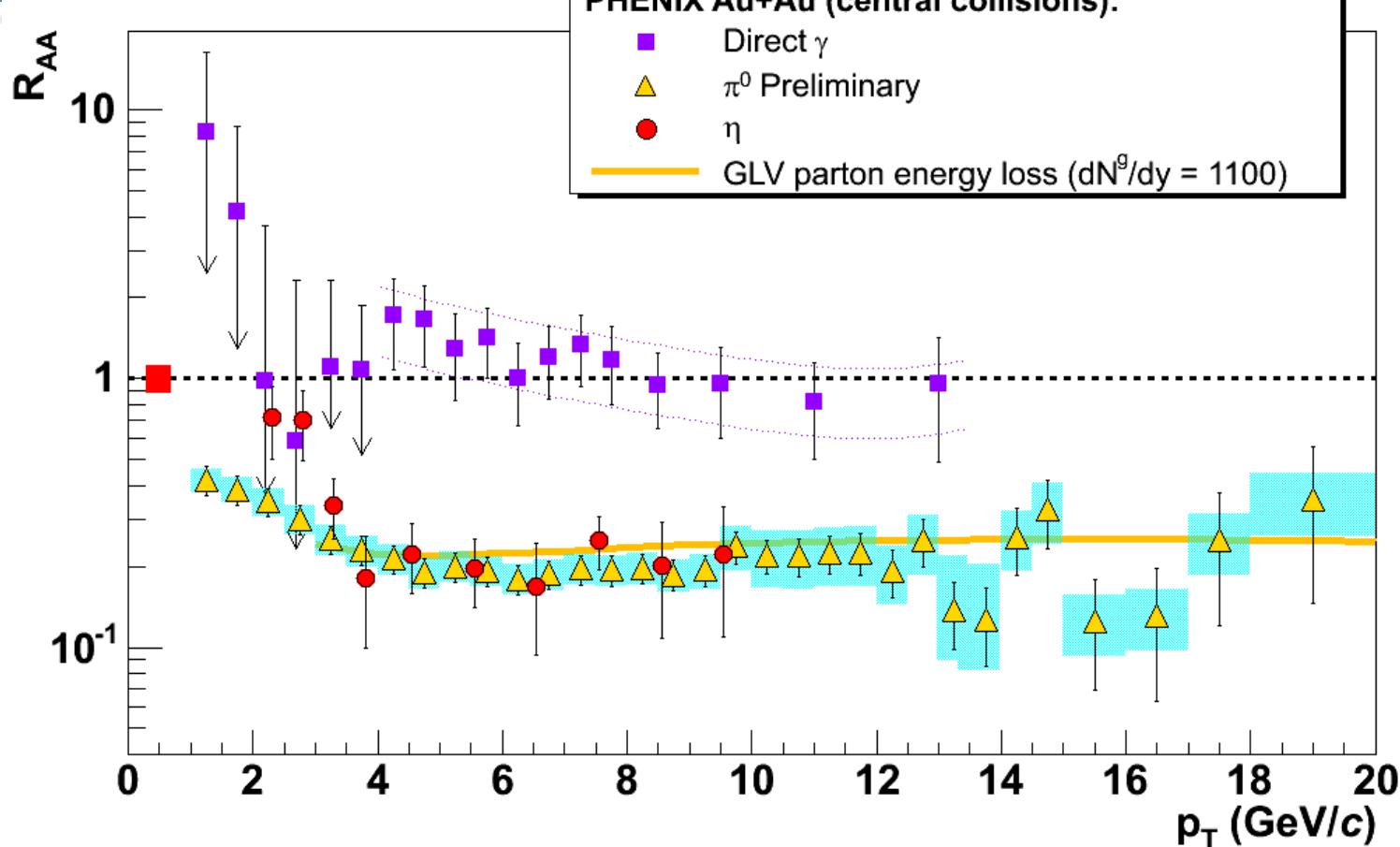


Experiment



- The medium should be transparent to photons.
- These thereby probe the initial rate of pQCD production and provide independent normalization of hard collision rates.

pQCD Photons!



- Data consistent with hard scattering at pQCD rates plus suppression.
- Jet Quenching again proves to be a final state effect!

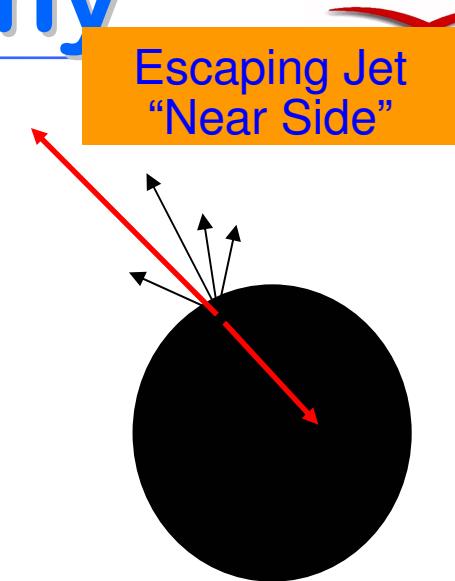
Jet Tomography

- Tomography, a fancy word for a shadow!
- Jets are produced as back-to-back pairs.
- One jet escapes, the other is shadowed.
- Expectation:
 - “Opaque” in head-on collisions.
 - “Translucent” in partial overlap collisions.

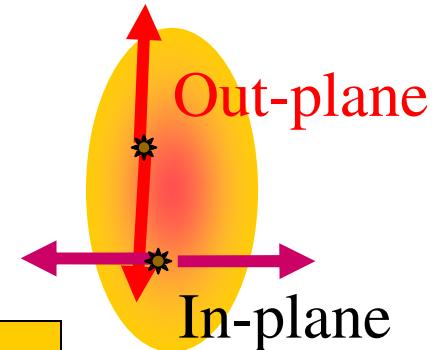


X-ray pictures are shadows of bones

Can Jet Absorption be Used to
“Take an X-ray” of our Medium?



Lost Jet
“Far Side”

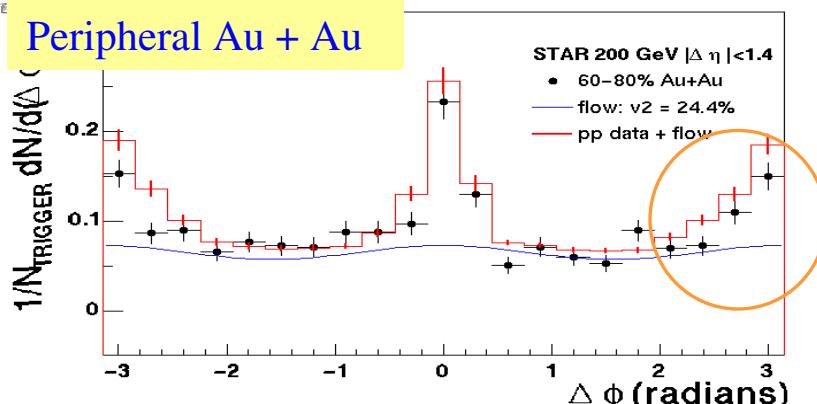


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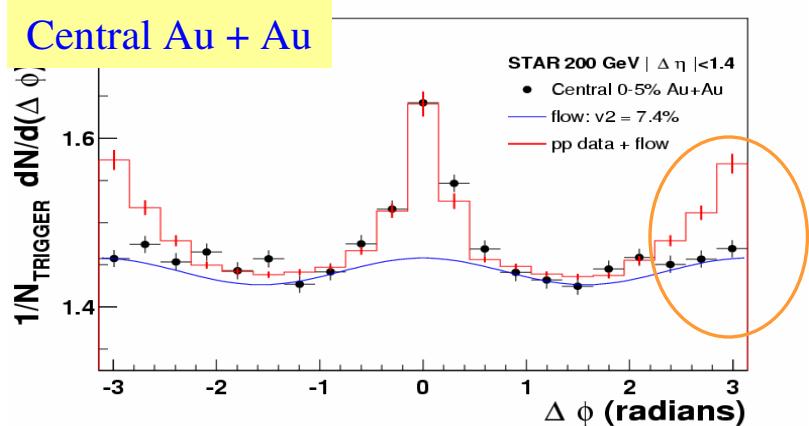
Back-to-back jets

STATE

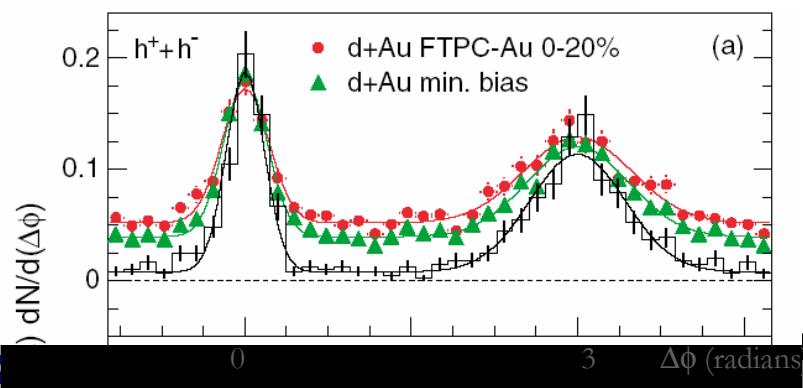
Peripheral Au + Au



Central Au + Au



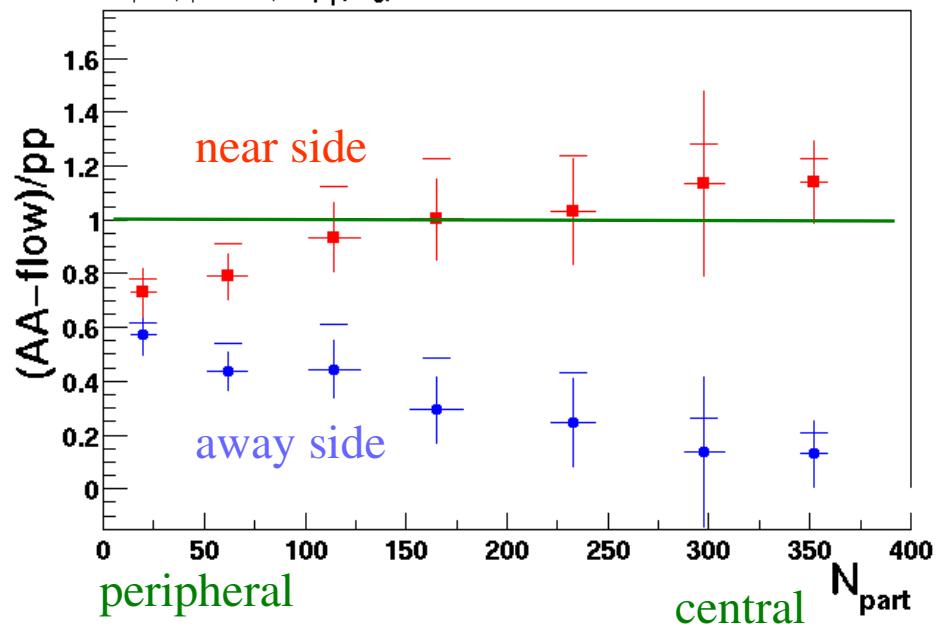
d + Au control



STAR PRL 90, 082302 (2003)

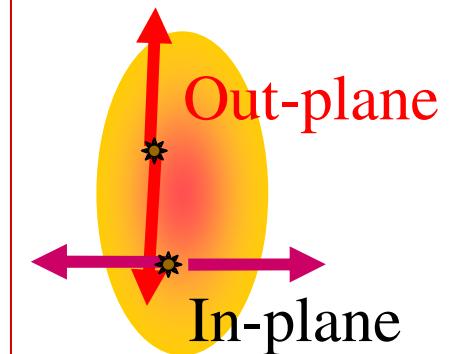
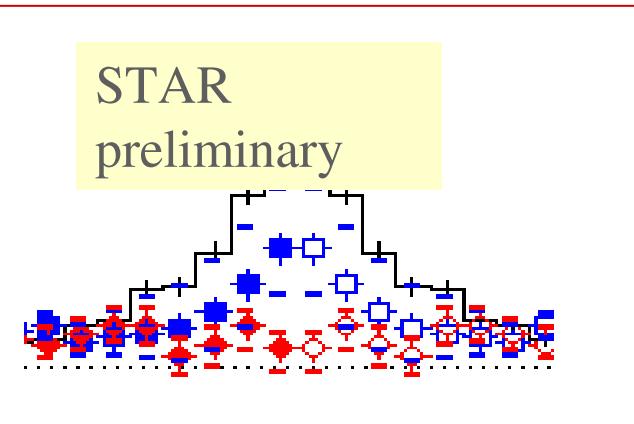
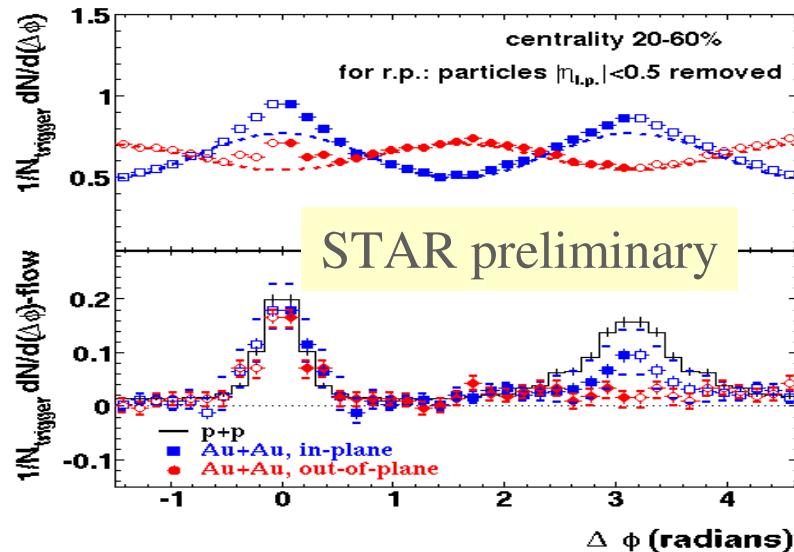
$$D_2(Au + Au) = D_2(p + p) + B(1 + v_2^2 \cos(2\Delta\phi))$$

- $|\Delta\phi| < 0.75, 4 < p_T(\text{trig}) < 6 \text{ GeV}/c$
- $|\Delta\phi| > 2.25, 4 < p_T(\text{trig}) < 6 \text{ GeV}/c$



- Away-side sensitive to precise v_2 value.
- Desire precision technique to disentangle v_2 .

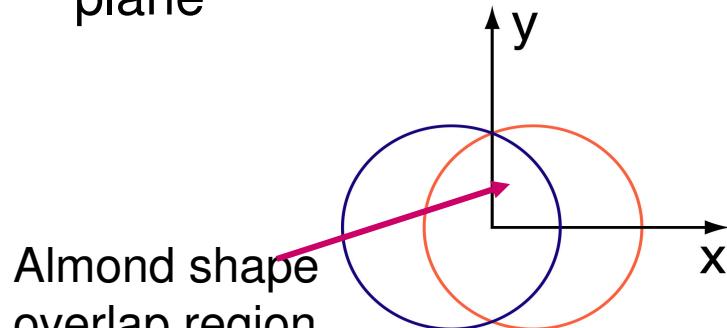
Back-to-Back wrt Reaction Plane



- Suppression stronger in the out-of-plane direction.
- Indicates suppression depends upon length of medium traversed.

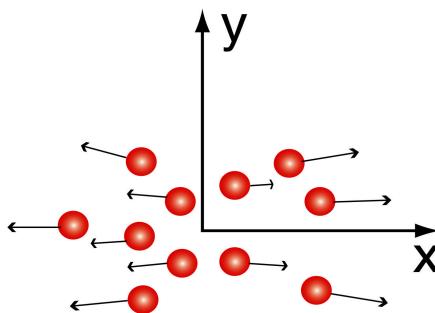
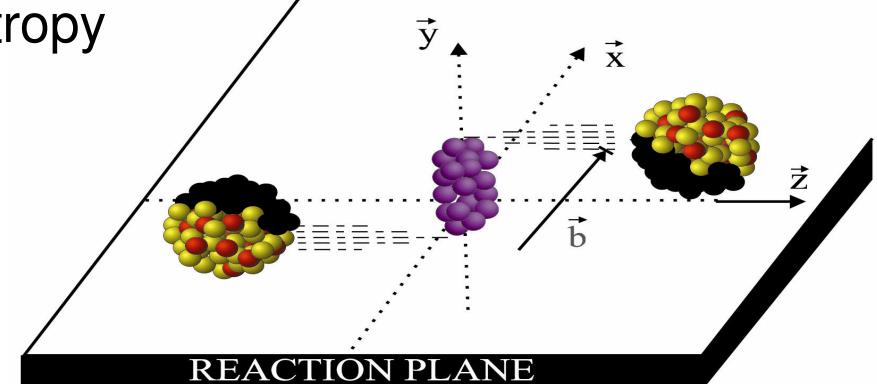
Origin: spatial anisotropy of the system when created, followed by multiple scattering of particles in the evolving system
 spatial anisotropy → momentum anisotropy

v_2 : 2nd harmonic *Fourier coefficient* in azimuthal distribution of particles with respect to the reaction plane



Almond shape overlap region in coordinate space

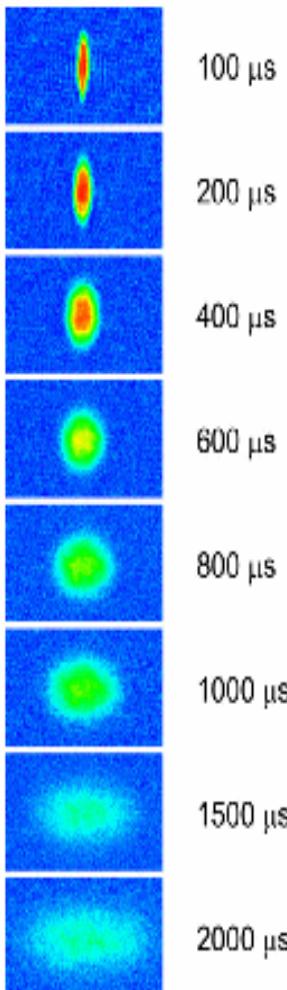
$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$



$$v_2 = \langle \cos 2\phi \rangle \quad \phi = \tan^{-1} \frac{p_y}{p_x}$$

Anisotropic Flow

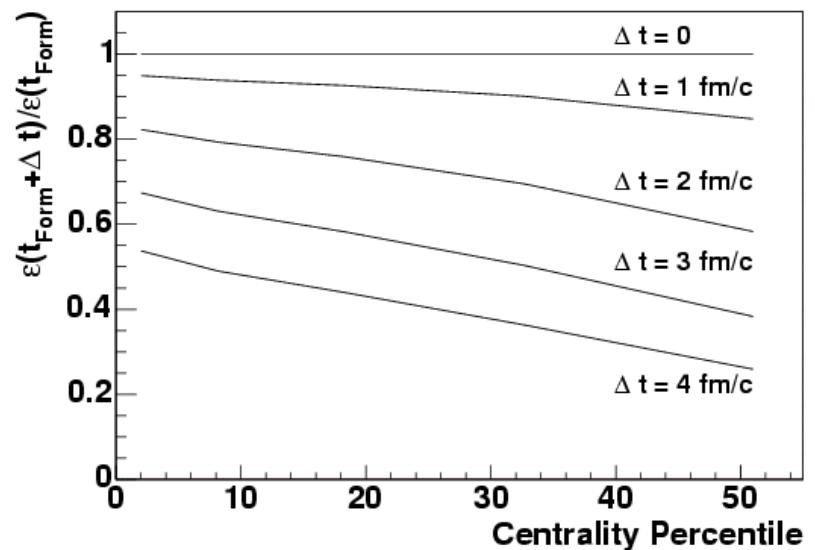
Liquid Li Exploses into Vacuum



Position Space anisotropy (eccentricity) is transferred to a momentum space anisotropy visible to experiment

- Gases explode into vacuum uniformly in all directions.
- Liquids flow violently along the short axis and gently along the long axis.
- We can observe the RHIC medium and decide if it is more liquid-like or gas-like

- Process is SELF-LIMITING
- Sensitive to the initial time



- Delays in the initiation of anisotropic flow not only change the magnitude of the flow but also the centrality dependence increasing the sensitivity of the results to the initial time.

- Most general expression for ANY invariant cross section uses explicit Fourier-Series for explicit ϕ dependence:

$$\frac{1}{p_T} \frac{d^3N}{dp_T d\phi dy} = \frac{1}{2\pi p_T} \frac{d^2N}{dp_T dy} [1 + 2v_1(p_T, y)\cos(\phi) + 2v_2(p_T, y)\cos(2\phi) + \dots]$$

here the sin terms are skipped by symmetry arguments.

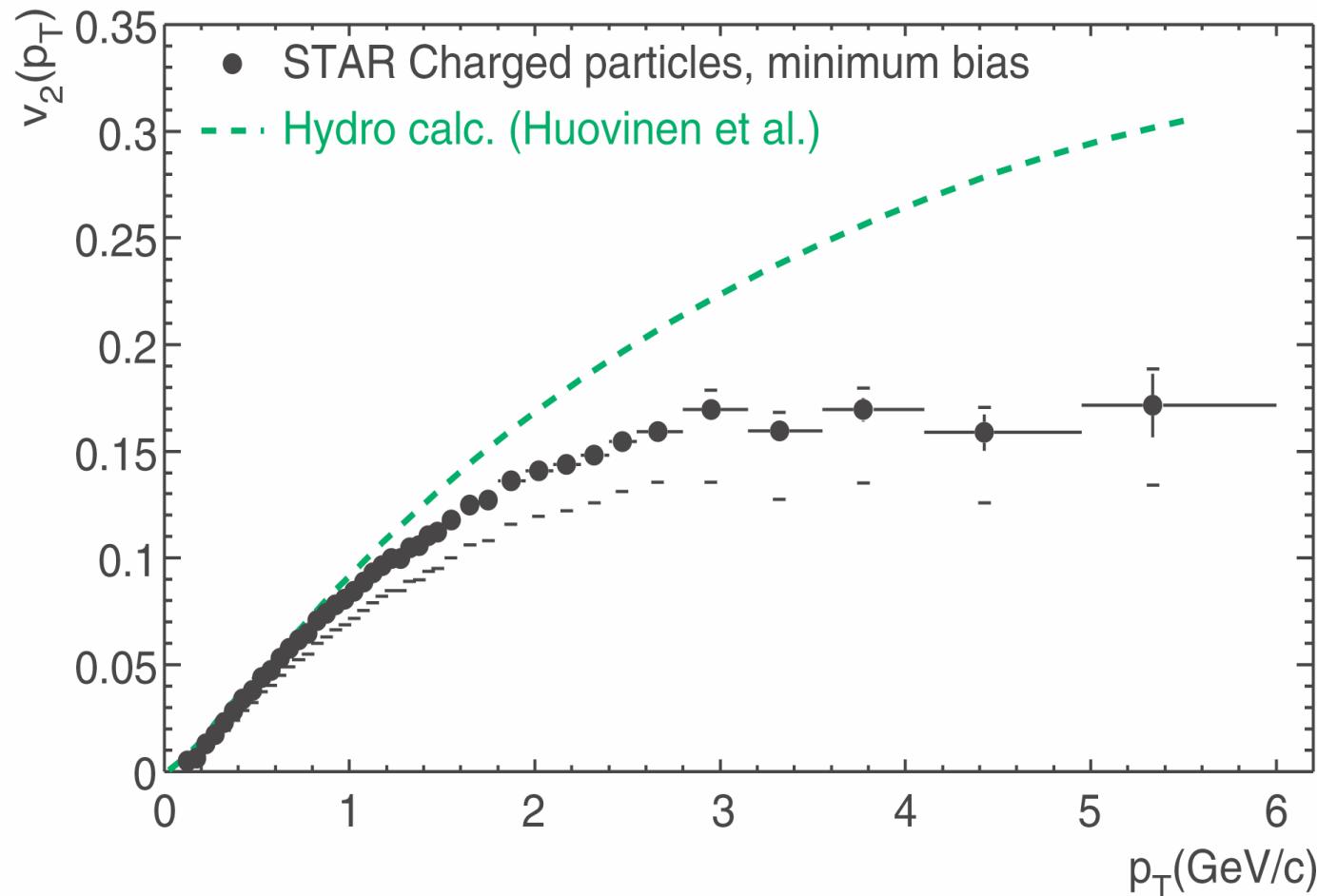
- For a symmetric system (AuAu, CuCu) at $y=0$, v_{odd} vanishes

$$\frac{1}{p_T} \frac{d^3N}{dp_T d\phi dy} = \frac{1}{2\pi p_T} \frac{d^2N}{dp_T dy} [1 + 2v_2(p_T)\cos(2\phi) + 2v_4(p_T)\cos(4\phi) + \dots]$$

- v_4 and higher terms are non-zero and measured but will be neglected for this discussion.

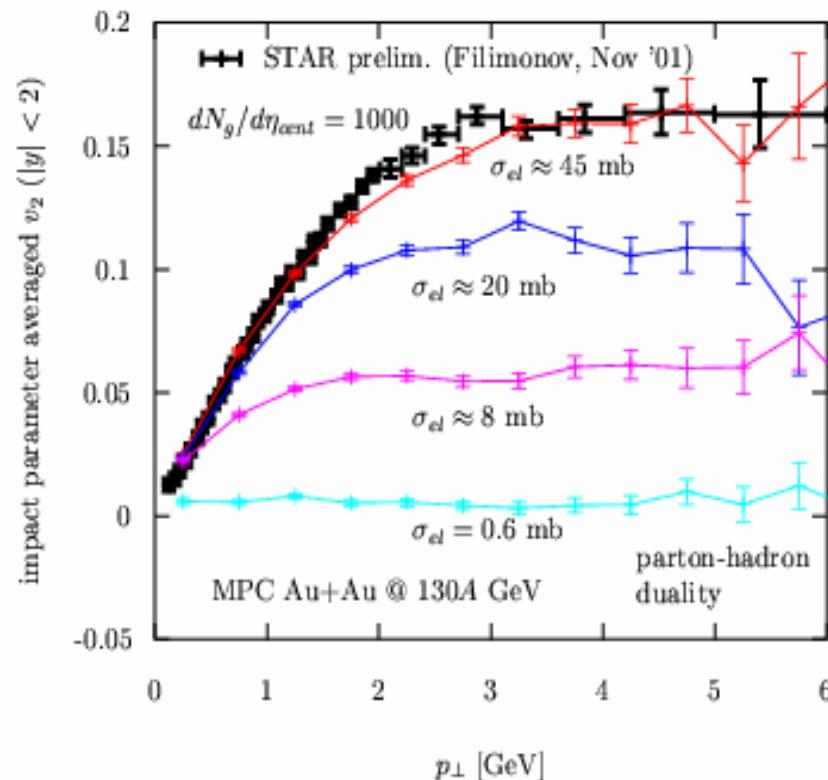
$$\frac{1}{p_T} \frac{d^3N}{dp_T d\phi dy} = \frac{1}{2\pi p_T} \frac{d^2N}{dp_T dy} [1 + 2v_2(p_T)\cos(2\phi)]$$

Just how big is v_2 ?



Yup, that's pretty big

Adler et al., nucl-ex/0206006



**parton transport solutions via
MPC 1.6.0** [D.M. & Gyulassy, NPA 697
('02)]

$$p^\mu \partial_\mu f_i = S_i + C_i^{2 \rightarrow 2}[f] + \dots$$

minijet initial conditions
 $1g \rightarrow 1\pi$ hadronization

Huge cross sections!!

- saturation pattern can be reproduced with elastic $2 \rightarrow 2$ interactions,
requires large opacities $\sigma_{el} \times dN_g/d\eta \approx 45000$ mb \gg pQCD (3 mb $\times 1000$)
- large opacities also suggested by pion HBT data [D.M & Gyulassy, nucl-th/0211017]

Splash!



Hydrodynamic Equations

$\partial_\mu T^{\mu\nu} = 0$, Energy-momentum conservation

$\partial_\mu n_i^\mu = 0$ Charge conservations (baryon, strangeness, etc...)

For perfect fluids (neglecting viscosity),

$$T^{\mu\nu} = (e + P)u^\mu u^\nu - Pg^{\mu\nu}$$

Energy density

Pressure

4-velocity

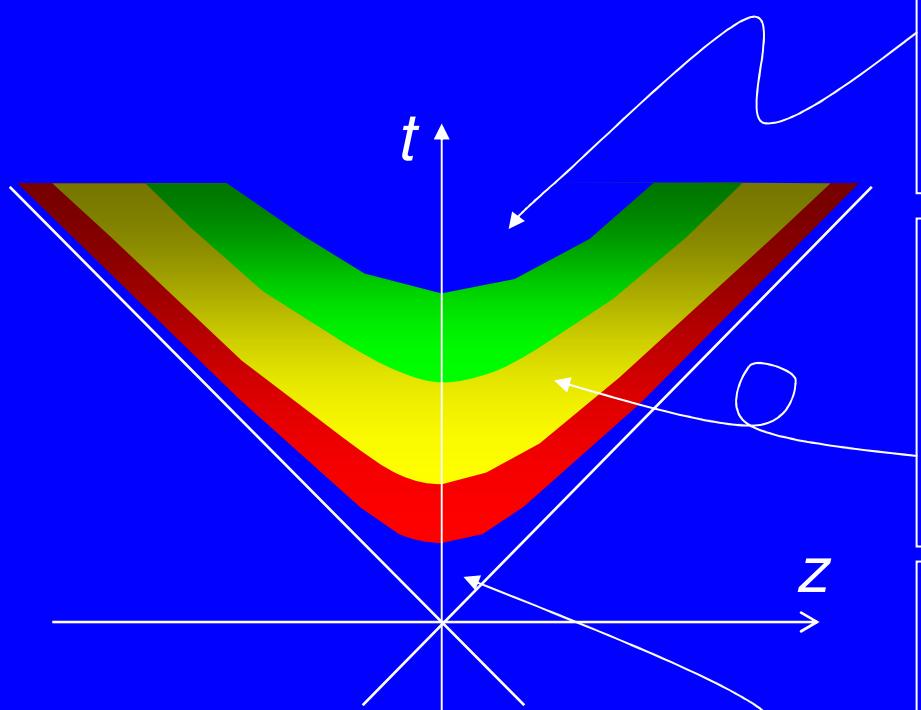
Need equation of state (EoS)
 $P(e, n_B)$
 to close the system of eqs.
 → Hydro can be connected directly with lattice QCD

Within ideal hydrodynamics, pressure gradient dP/dx is the driving force of collective flow.

- Collective flow is believed to reflect information about EoS!
- Phenomenon which connects 1st principle with experiment

Caveat: Thermalization, $\lambda_{42} \ll$ (typical system size)

Inputs to Hydrodynamics



Need modeling
(1) EoS, (2) Initial cond.,
and (3) Decoupling

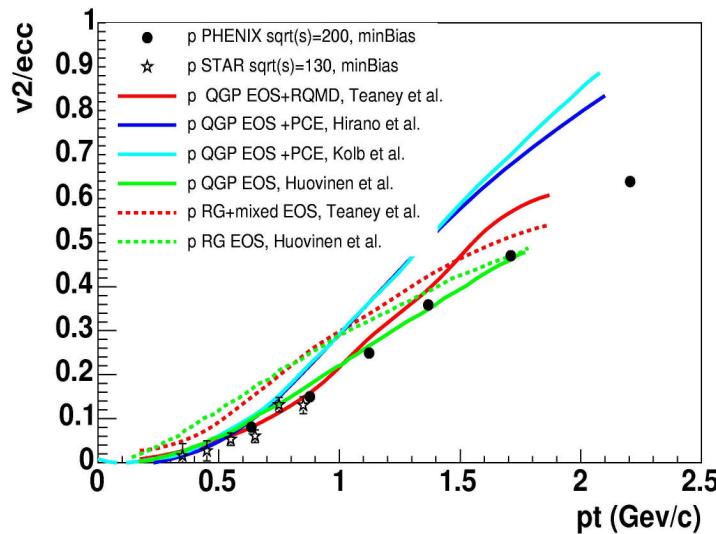
Final stage:
Free streaming particles
→ Need decoupling prescription

Intermediate stage:
Hydrodynamics can be valid
if thermalization is achieved.
→ Need EoS

Initial stage:
Particle production and
pre-thermalization
beyond hydrodynamics
→ Instead, initial conditions
for hydro simulations

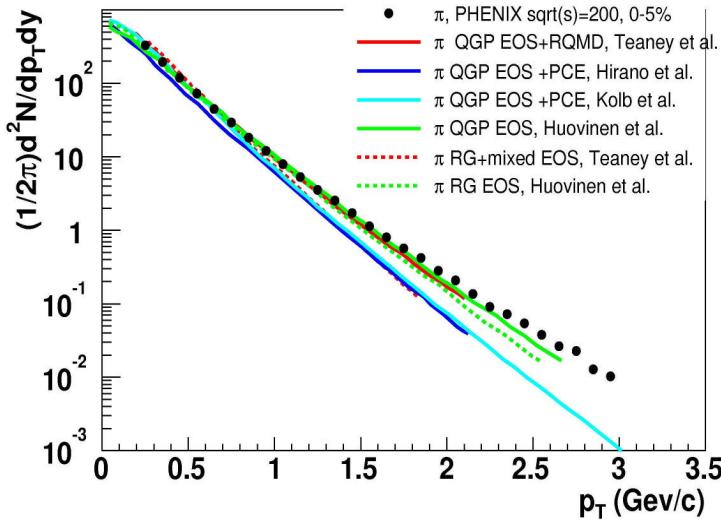
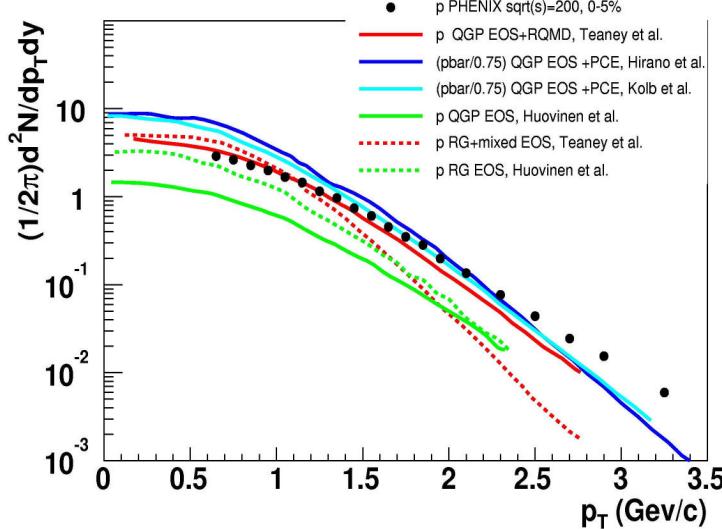
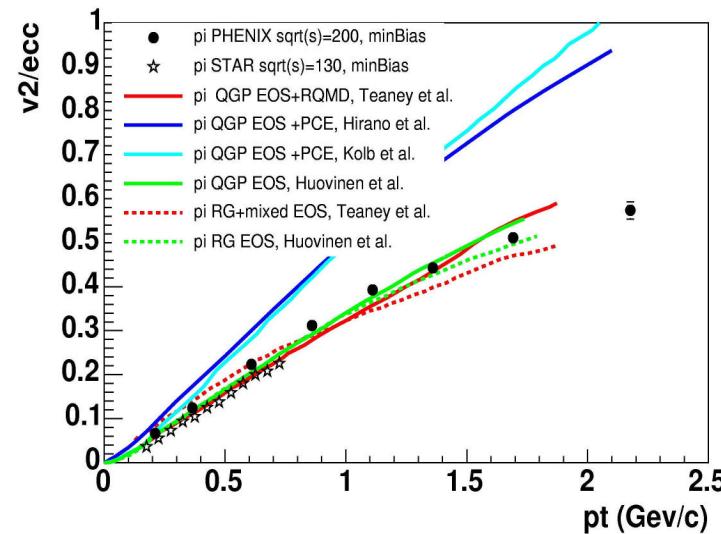
v_2 - AND- spectra

proton



pion

nucl-ex/0410003



Hydro models:
Teaney
(w/ & w/o
RQMD)

Hirano
(3d)

Kolb

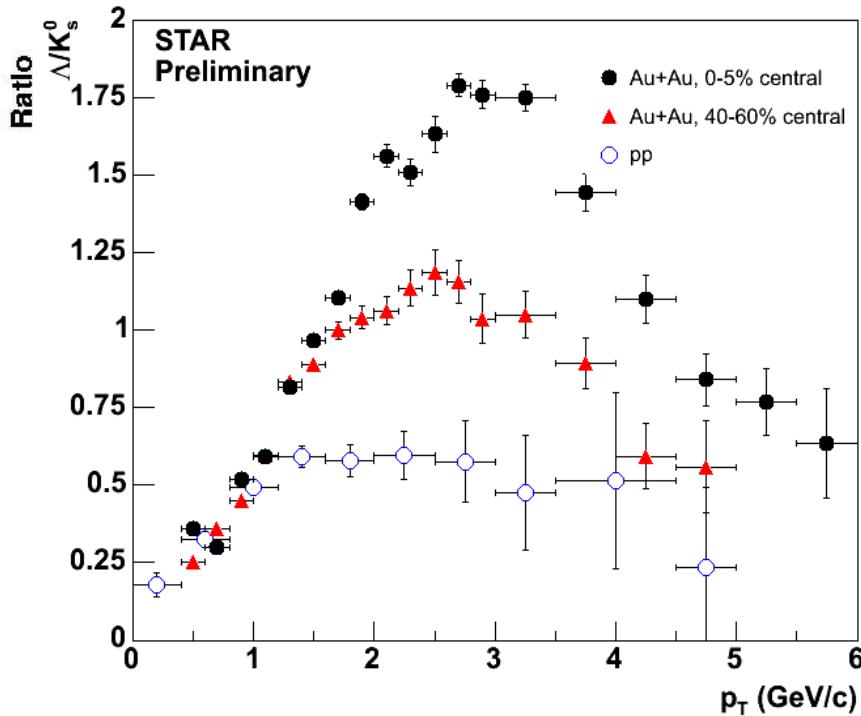
Huovinen
(w/ & w/o
QGP)

	QGP+mixed+RG				mixed+RG	RG
	Teaney	Hirano	Kolb	Huovinen	Teaney	Huovinen
latent heat (GeV/fm ³)	0.8	1.7	1.15	1.15	0.8	1.15
init. ϵ_{max} (GeV/fm ³)	16.7		23	23	16.7	23
init. $\langle \epsilon \rangle$ (GeV/fm ³)	11.0	13.5			11.0	
τ_0 fm/c	1.0	0.6	0.6	0.6	1.0	0.6
hadronic stage	RQMD	partial chemical equil.	partial chemical equil.	full equil.	RQMD	full equil.
proton v2	yes	< 0.7 GeV/c	< 0.7 GeV/c	yes	no	no
pion v2	yes	no	no	yes	yes	yes
proton spectra	yes	overpredict	overpredict	no	no	no
pion spectra	yes	< 1 GeV/c	< 1 GeV/c	yes	< 0.7 GeV/c	yes
HBT	Not available	No	Not available	No	Not available	Not available

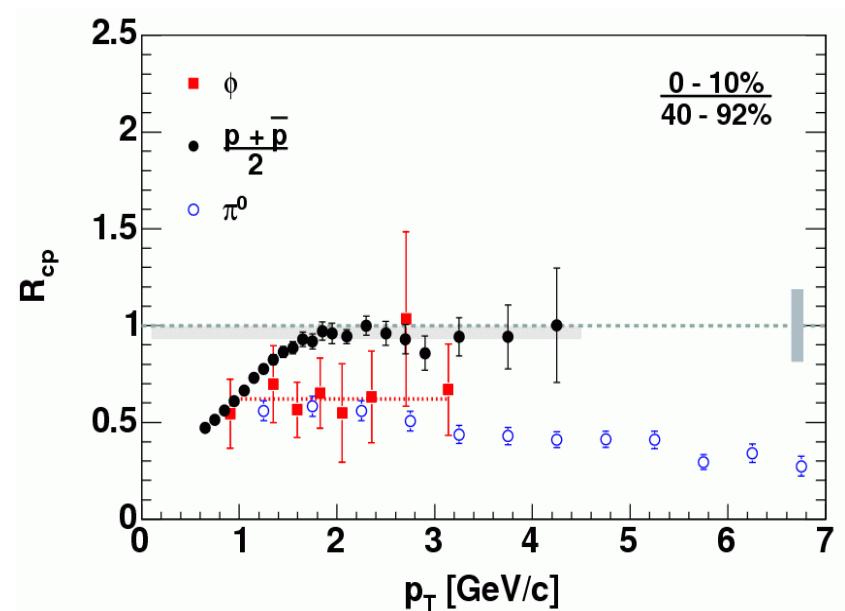
- The hydro-models which include both hadronic and QGP phases reproduce the qualitative features of the measured $v_2(p_T)$ of pions, kaons, and protons.
- These hydro-models require an early thermalization ($\tau_{therm} < 1 \text{ fm/c}$) and high initial energy density $\epsilon > 10 \text{ GeV/fm}^3$
- Several of the hydro-models fail to reproduce the v_2 and spectra simultaneously.
- HBT source parameters are not reproduced by any hydrodynamic calculations.

The RHIC data are consistent with the so-called “Hydrodynamic Limit” for a non-viscous relativistic

Large p/π ratio in 2-4 GeV/c



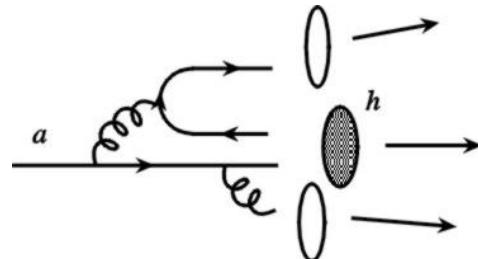
Proton scales with N_{coll}
Mesons don't



- Large excesses of baryons are observed at intermediate p_T .
- Why is this not just the flow we discussed yesterday?
 - Flow generates spectral differences based purely on mass.
 - We shall see later that this new effect depends not upon mass but valence quark count.

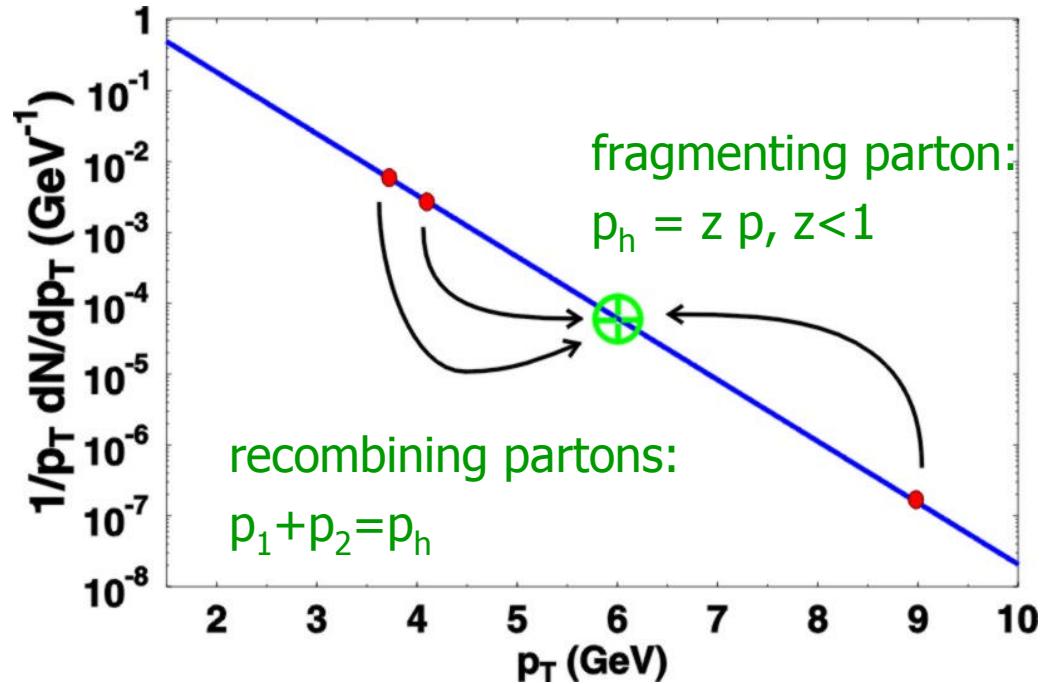
Recombination Concept

Fragmentation:



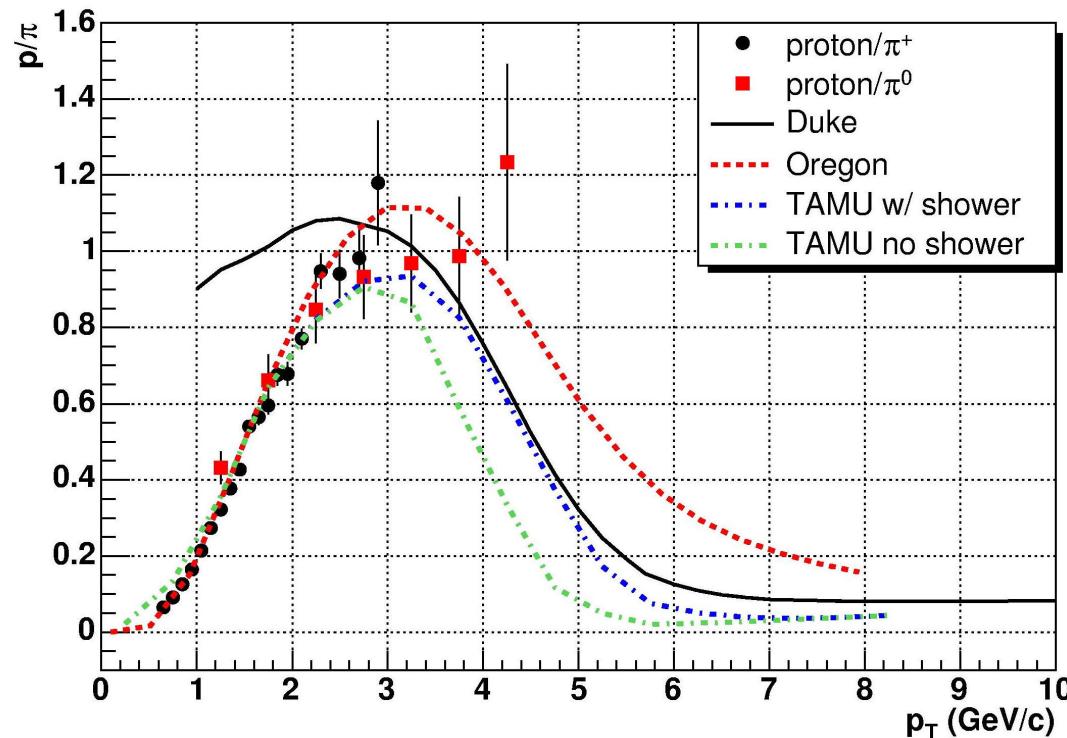
$$E \frac{dN_h}{d^3 P} = \int_0^1 \frac{dz}{z^2} \frac{E}{z} \frac{dN_a}{d^3(P/z)} D_{a \rightarrow h}(z)$$

- for exponential parton spectrum, recombination is more effective than fragmentation
- baryons are shifted to higher p_T than mesons, for same quark distribution
 - understand behavior of protons!



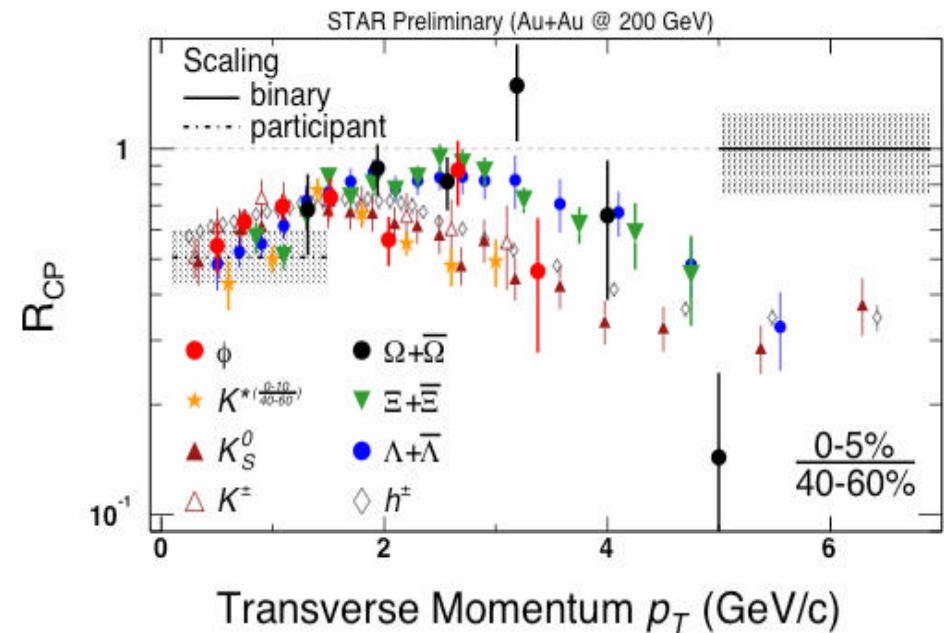
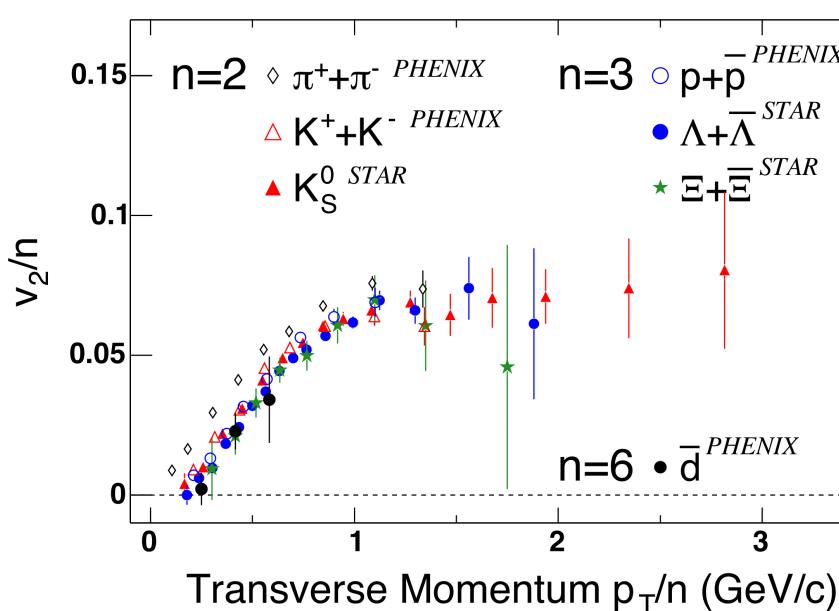
Recombination Models

PHENIX proton/ π ratio



- Duke:
 - Pure thermal reco.
- Oregon:
 - Fragmentation itself is recast as a recombination process. HI collision simply adds extra thermal quarks during the process.
- TAMU:
 - Jets and also feeddown from resonances.

Recombination Scaling

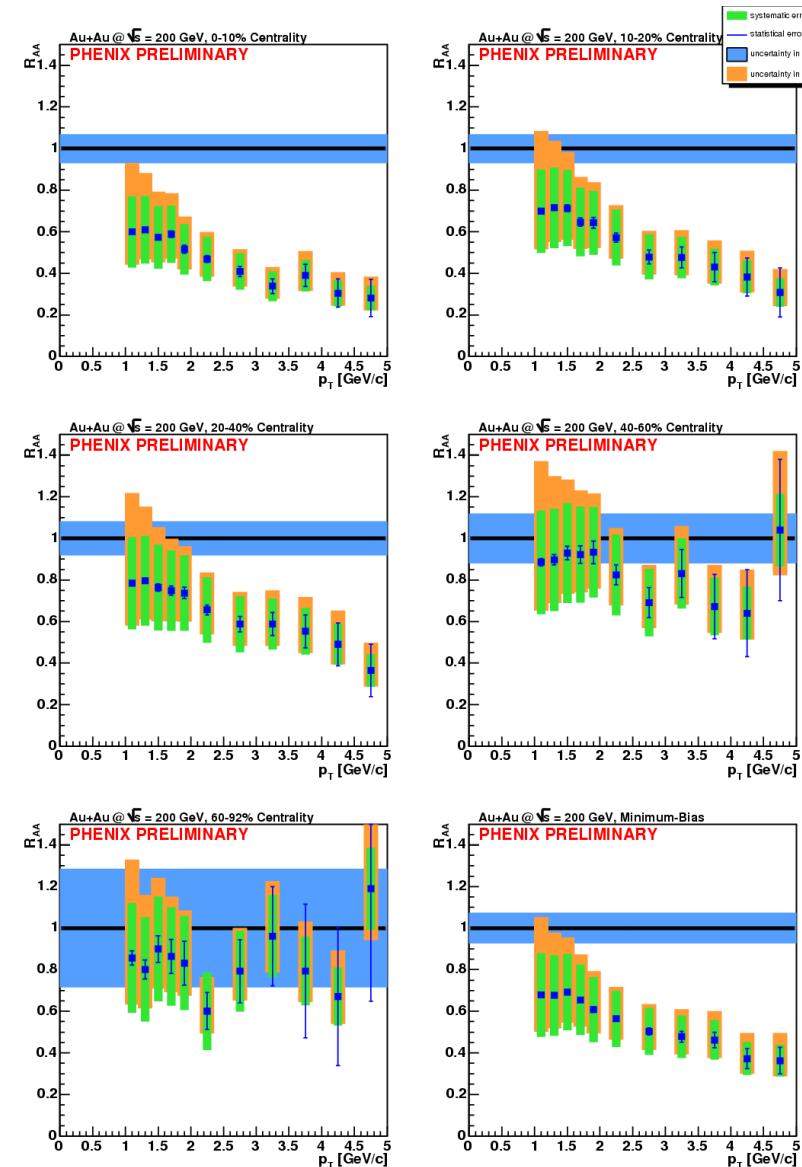


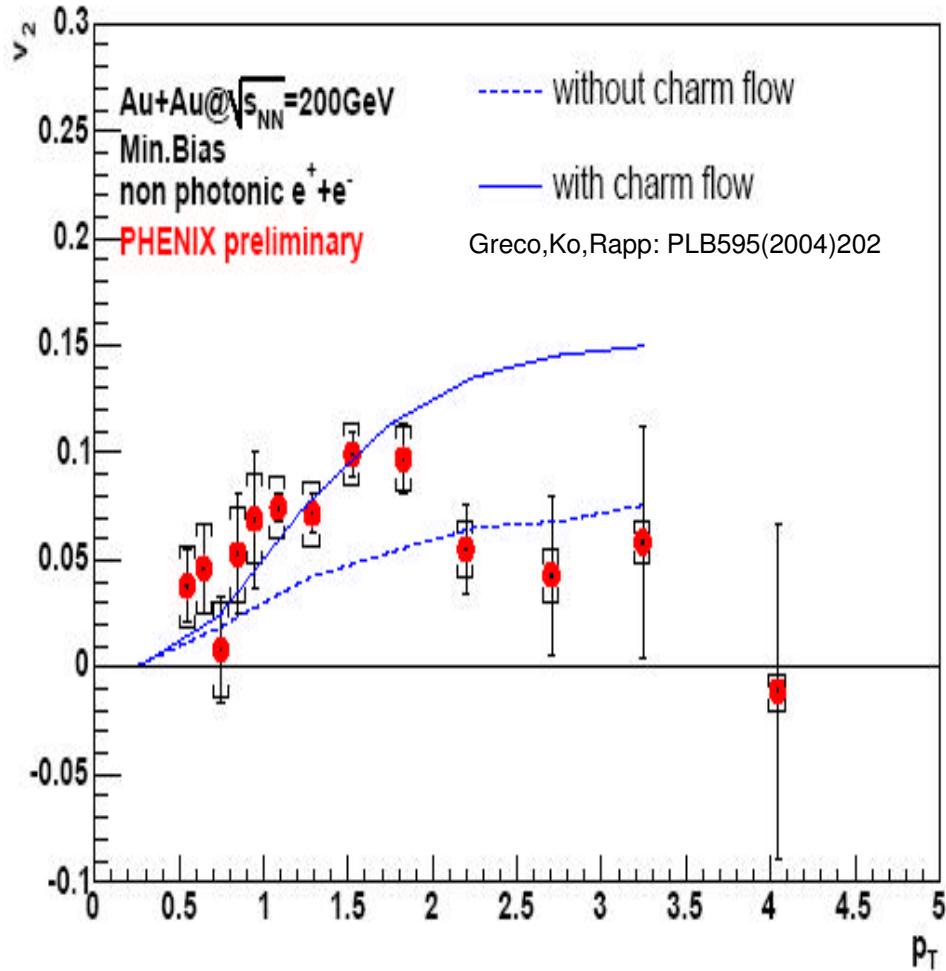
- The nuclear modification factor when plotted for many particle species shows a bifurcation based upon **VALENCE QUARK COUNT** (not mass).
- The flow patterns for all particles (except pions) are identical when scaled by valence quark count

HOT#1-- R_{AA} of charm electrons

*clear
evidence for
energy loss of
charm quarks
in central
 $Au + Au$!
(NOTE: Likely to
also be some
 e^\pm from B decays)*

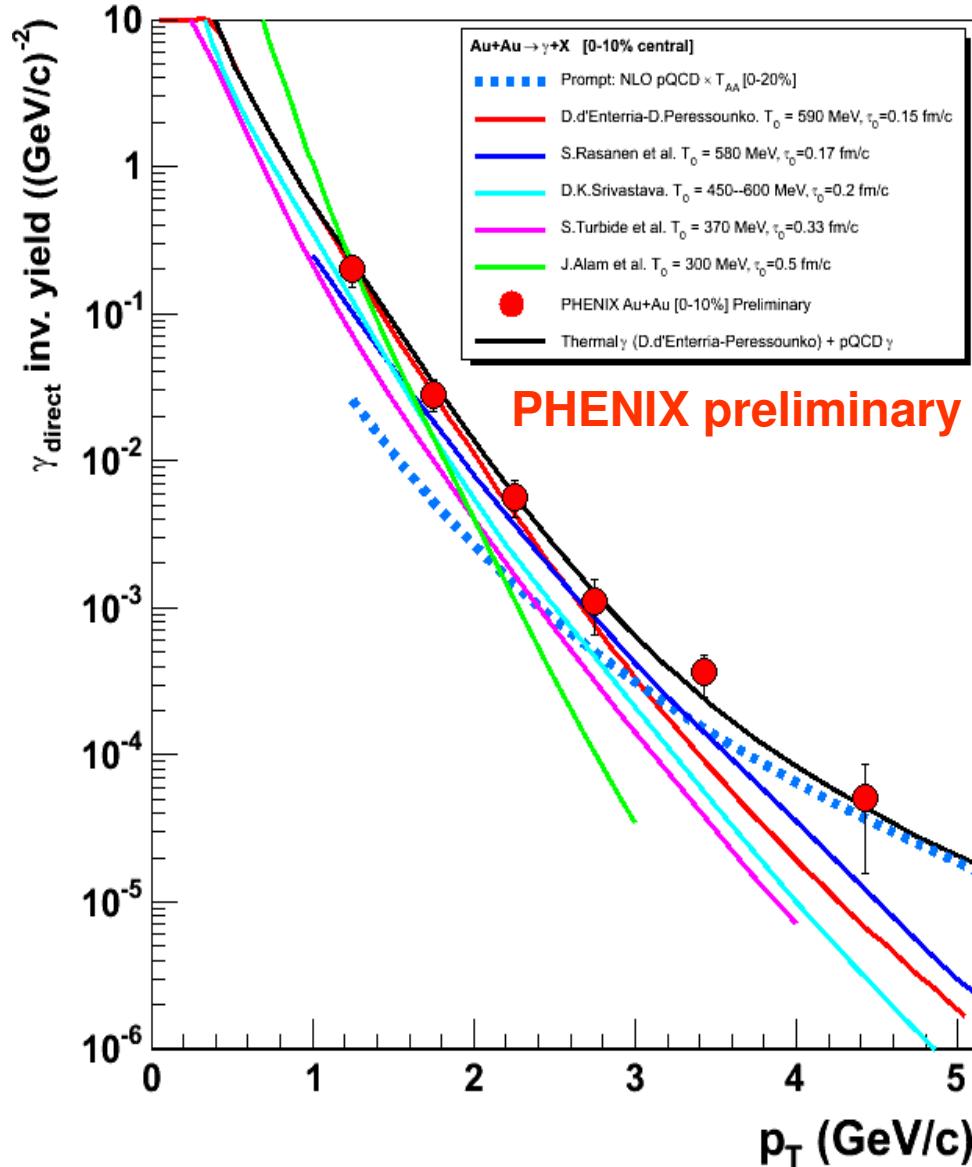
R_{AA}





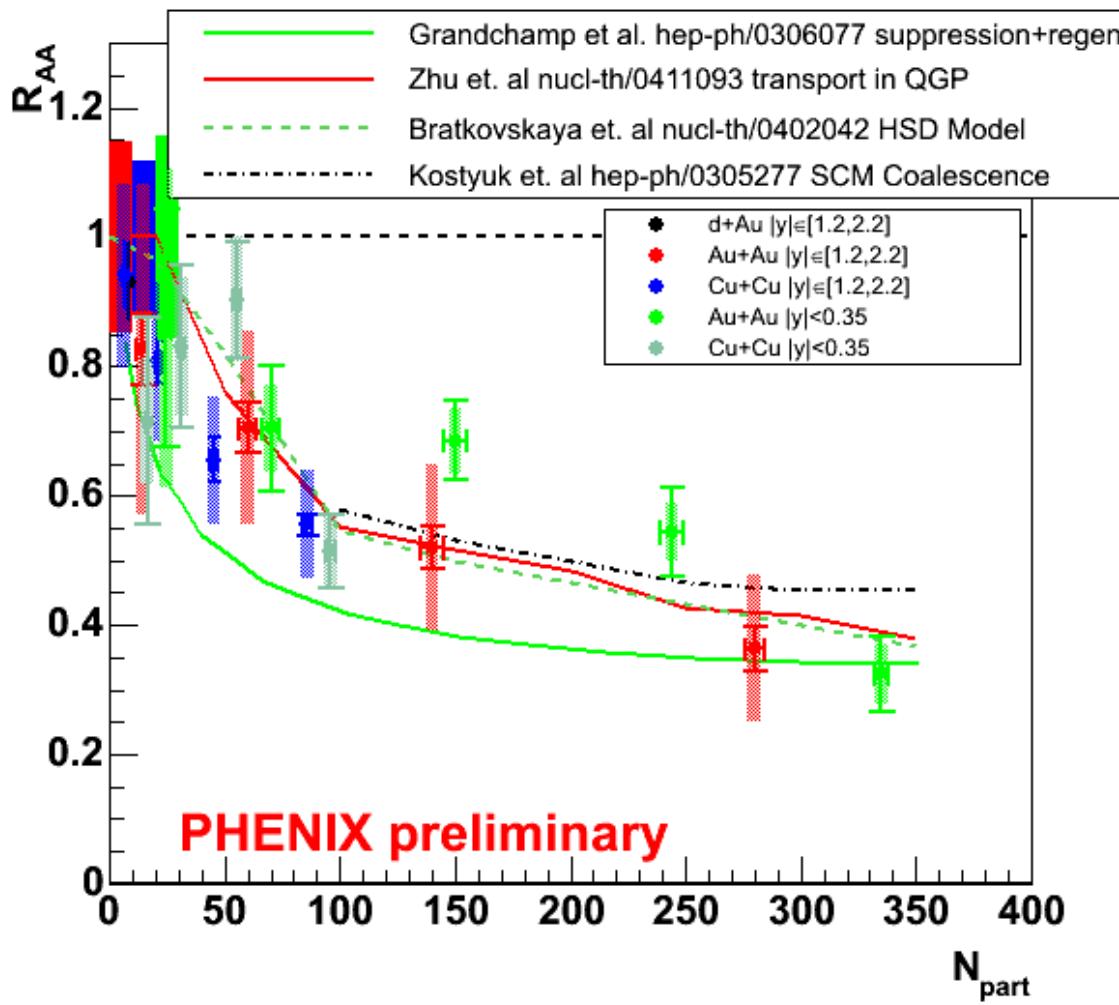
- Charm flows, but not as strong as light mesons.
- Drop of the flow strength at high p_T . Is this due to b-quark contribution?
- The data favors the model that charm quark itself flows at low p_T .
- Charm flow supports high parton density and strong coupling in the matter. It is not a weakly coupled gas.

Hot #3--(thermal?) photons



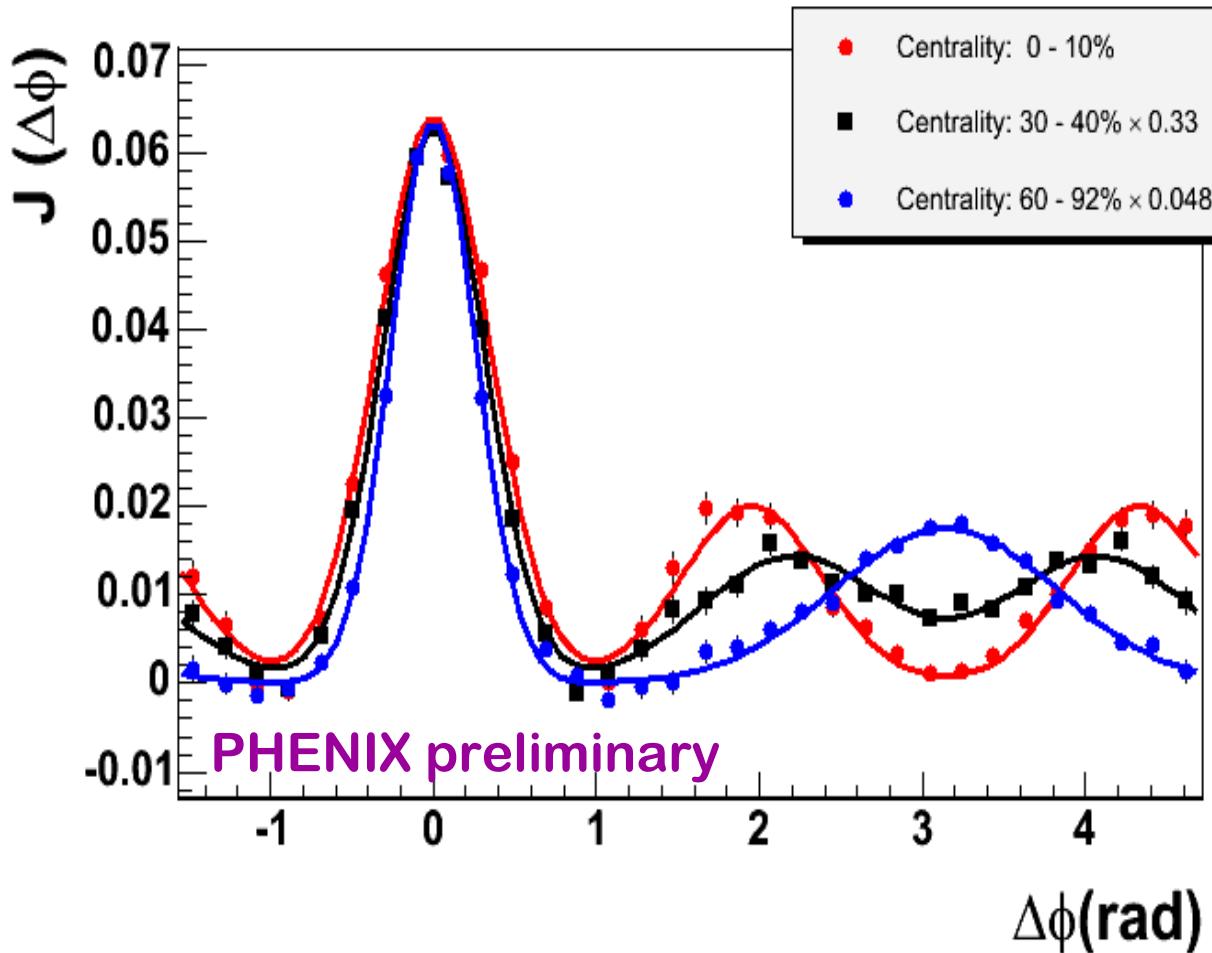
- The first promising result of direct photon measurement at low p_T from low-mass electron pair analysis.
- Are these thermal photons? The rate is above pQCD calculation. The method can be used in $p+p$ collisions.
- If it is due to thermal radiation, the data can provide the first direct measurement of the initial temperature of the matter.
- $T_0^{\max} \sim 500\text{--}600$ MeV !?
- $T_0^{\text{ave}} \sim 300\text{--}400$ MeV !?

J/ ψ nuclear modification factor R_{AA}



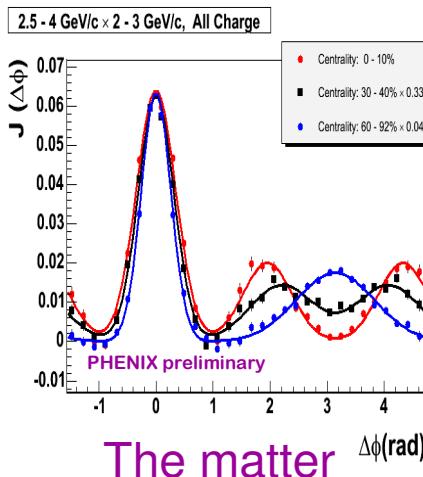
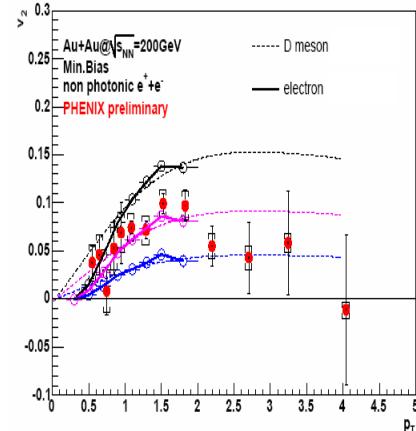
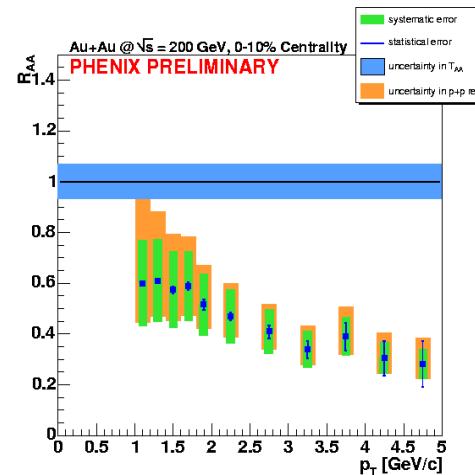
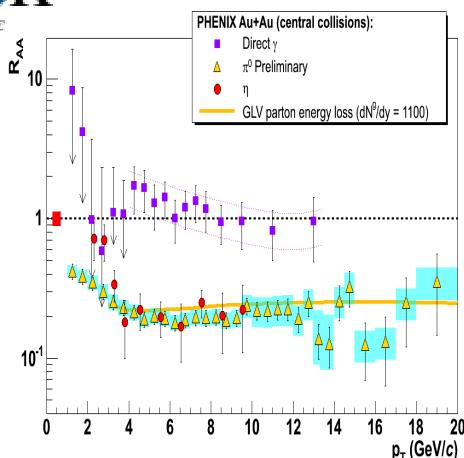
- J/ ψ 's are clearly suppressed beyond the cold nuclear matter effect
- The preliminary data are consistent with the predicted suppression + re-generation at the energy density of RHIC collisions.
- Can be tested by $v_2(J/\psi)$?

2.5 - 4 GeV/c \times 2 - 3 GeV/c, All Charge



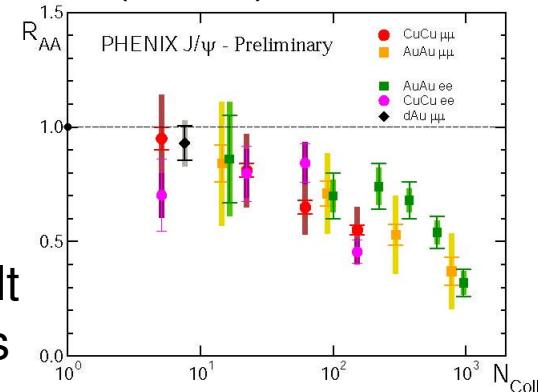
- The shapes of jets are modified by the matter.
 - Mach cone?
 - Cerenkov?
- Can the properties of the matter be measured from the shape?
 - Sound velocity
 - Di-electric constant
- Di-jet tomography is a powerful tool to probe the matter

All Together Now:



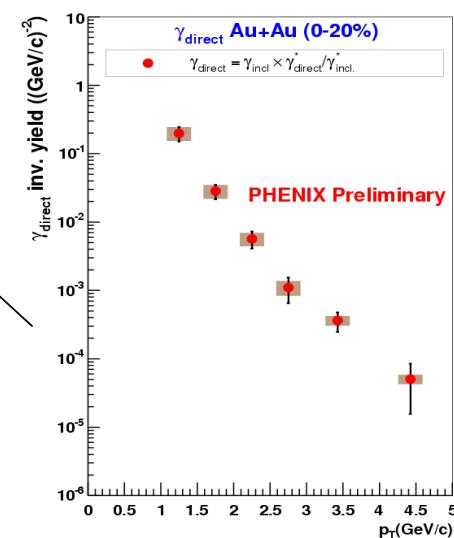
The matter
modifies jets

The matter is dense
 We are now working
 with the theory
 community to extract the
 properties of the matter
 $e > 15$ GeV/fm³
 $dN/dy > 1100$
 $T_{ave} = 300 - 400$ MeV (?)
 $V_s = ?$
 $\epsilon(\text{dielec}) = ?$



The matter may melt
but regenerate J/ ψ 's

Stony Brook University



The matter is hot

Thomas K. Hemmick